ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS

EDITOR: ALAN MARA BATEMAN
Yale University, New Haven, Connecticut

BUSINESS EDITOR: MORRIS M. LEIGHTON
Illinois Geological Survey, Urbana, Illinois

ASSISTANT EDITORS

H. E. MCKINSTRY, *Harvard University*
JOE W. PEOPLES, *Wesleyan University*
F. M. CHACE, *U. S. Geological Survey*
J. D. BATEMAN, *Yellowknife, N.W.T.*
R. H. JAHNS, *California Institute of Technology, Pasadena*

ASSOCIATE EDITORS

CHARLES KENNETH LEITH
University of Wisconsin, Madison, Wis.

D. F. HEWETT
U. S. Geological Survey, Washington, D. C.

A. I. LEVORSEN
Department of Geology, Stanford University, Calif.

B. S. BUTLER
Univ. of Arizona, Tucson, Ariz.

W. E. WRATHER
U. S. Geological Survey, Washington, D. C.

HEINRICH RIES
Cornell University, Ithaca, N. Y.

L. C. GRATON
Harvard University, Cambridge, Mass.

E. S. MOORE
Royal Ontario Museum, Toronto, Can.

PER GEIJER
Geological Survey of Sweden, Stockholm, Sweden

P. F. FOURMARIER
Liège University, Liège, Belgium

M. S. KRISHNAN
Geological Survey, Calcutta, India

DJALMA GUIMARÃES
Instituto de Tecnologia Industrial Belo Horizonte, Minas Gerais, Brazil

T. W. GEVERS
University of the Witwatersrand, Johannesburg, S. Africa

A SEMI-QUARTERLY JOURNAL PUBLISHED BY
THE ECONOMIC GEOLOGY PUBLISHING COMPANY

SOCIETY OF ECONOMIC GEOLOGISTS

THE PUBLICATIONS OF WHICH CONSTITUTE
A PART OF THIS JOURNAL

OFFICERS FOR 1950

MORRIS M. LEIGHTON.....*President*
IRA B. JORALEMON....*Vice President and President elect*
T. B. NOLAN.....*Past President*
ANTON GRAY....*Vice President elect*
OLAF N. ROVE.....*Secretary*
U. S. Geological Survey, Washington 25, D. C.
JOSEPH T. SINGEWALD, JR...*Treasurer*
Johns Hopkins Univ., Baltimore, Md.

Councilors

1950	*1951*	*1952*
CARLTON D. HULIN	PHILIP J. SHENON	H. M. BANNERMAN
DONALD DAVIDSON	ANDREW LEITH	JOHN S. BROWN
WILLIAM CALLAHAN	JOHN GUSTAFSON	CHARLES F. PARK, JR.

Regional Vice-Presidents

OLAF H. ODMAN, Europe.....CHINGYUAN Y. LI, Asia.....
TARRAN GUERNSEY, Africa...VICTOR DOLMAGE, North America...
H. C. ALVES DE SOUZA, South America....N. H. FISHER, Australia.

Executive Committee

MORRIS M. LEIGHTON, *Chairman* — T. B. NOLAN, OLAF N. ROVE, IRA B. JORALEMON, JOSEPH T. SINGEWALD, JR.

Finance Committee

WILLIAM CALLAHAN, *Chairman* — W. O. HOTCHKISS, JOSEPH T. SINGEWALD, JR., T. B. NOLAN

Program Committee

CHAS. F. DEISS, *Chairman* — JAMES A. NOBLE, GEORGE W. WHITE, OLAF N. ROVE, DONALD DAVIDSON

Committee on Publications

EUGENE N. CAMERON, *Chairman* — EDWARD L. CLARK, H. E. MCKINSTRY

Nominating Committee

CHARLES F. PARK, JR., *Chairman* — H. M. BANNERMAN, GEORGE M. FOWLER

Admissions Committee

A. C. BEVAN, *Chairman* — PHILIP J. SHENON, H. G. HERSHEY, J. E. HAWLEY, F. C. KRUGER

Auditing Committee

FRANCIS G. WELLS, *Chairman* — A. NELSON SAYRE

Coal Research Committee

Executive Members: G. H. Cady, *Chairman*, Paul Averitt, Clayton G. Ball

ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF
ECONOMIC GEOLOGISTS

VOL. 46 MARCH–APRIL, 1951 NO. 2

COPPER MINERALIZATION IN THE FUNGURUME REGION, KATANGA.

R. OOSTERBOSCH.

WITH AN INTRODUCTION BY

H. SCHUILING.

ABSTRACT.

The copper and cobalt sulfide mineralization of Katanga occurs in two dolomitic formations, which are slightly metamorphic and are probably of Precambrian age. The present study relates to one of these formations in the Fungurume region. It consists of semi-competent beds in contact with competent beds, and the distribution of the mineralization is related to the type of their deformation. The beds were favorable for the introduction of mineralizing solutions.

The primary sulfides, bornite and carrollite, appear to replace the dolomite. The bornite is partly replaced by chalcocite of two types, namely, white and blue, but it is impossible definitely to recognize primary chalcocite because of the deep penetration of secondary chalcocite. Mineralization and silicification are rather closely related but different in details. There is no evidence of association of the mineralization with intrusives. The author weighs the evidence favoring syngenetic and epigenetic origin of the mineralization.

INTRODUCTION.

H. SCHUILING.

THE cupriferous basin of Katanga consists geologically of an apparently continuous sedimentary series that may be called the "Katanga System," the age of which has not been determined. The strata accumulated in a geosyncline and were folded prior to Upper Carboniferous time. This sedimentary series, which, in general, shows only epizonal metamorphism, is shown diagrammatically from top to bottom as follows:

Kundelungu series (or system)	3,000 m
Large conglomerate of Kundelungu (tillite) down to	300 m
Dolomitic shale series (position of base unknown in the center of the basin). Includes:	
An upper series of Mwashya series	100 to 500 m
A lower series or Mine Series	

The lower series of dolomitic shales has not been observed in normal contact with the Mwashya series but is everywhere so faulted that a reliable stratigraphic section has not been made. It is this series that contains formations that carry the cupro-cobalt mineralization, both primary and secondary, and which is called the "Mine Series." The Mine Series consists of dolomite beds —some of which are very siliceous—well-stratified, and form a tectonically competent group. This competent group appears to be between a complex of more or less arenaceous dolomite much contorted, called "argillo-talcose rocks" (R.A.T.), and an upper dolomite complex distinguishable with difficulty from the argillo-talcose rocks, having a variable facies, in places arenaceous, and which has been called "upper sandstone rocks" (R.G.S.).

In the Fungurume region, and more particularly in the eastern part of this region, the Mine Series is constituted as follows from top to bottom:

Dolomitic limestones, called "black ore limestones" (C.M.N.)	70 m
Dolomitic shales (S.D.)	120 m
Siliceous dolomites, partly organogenic (algae), massive, of coarse texture, called "cellular siliceous rocks" from the character of the weathered surface (R.S.C.)	20 m
Laminated siliceous dolomites, called "laminated siliceous rocks" (R.S.F.)	5 m
Stratified dolomites, microgranitic, called "stratified argillo-talcose rocks" on account of the surface alteration	3.50 m
Dolomitic chloritic arenaceous shale, called "gray argillo-talcose rocks"	0.20 m

The deformations have produced within the mining basin a group of regular synclines that are more or less made up of the Mwashya and Kundelungu Series. In the anticlinal zones, which are generally faulted and even overthrust, the Mine Series appears as foliations. These foliations are surrounded by breccia formed at the expense of either R.A.T. or R.G.S.

The mineralization, principally copper with lesser cobalt, is mainly confined to the "Mine Series" and to well-defined horizons of that series. The two main ore bodies are on both sides of the cellular siliceous rocks and immediately in contact with that rock. The upper or "first ore body" extends over several meters in thickness at the base of the "dolomitic shales." The lower or "second ore body" comprises all of the "laminated siliceous rock" and the "stratified argillo-talcose rock." The present study is concerned with the drilling of the second ore body.

Figure 1 shows the plan of the entire region of Fungurume; Figure 2 shows the position of the ore bodies in a diagrammatic structure section.

DIRECTOR, GEOLOGICAL DIVISION,
UNION MINIÈRE DU HAUT-KATANGA,
JADOTVILLE, BELGIAN CONGO.

THE "SECOND ORE BODY" OF FUNGURUME.

Stratigraphy and Detailed Petrographic Description.

The second ore body of Fungurume consists of stratified dolomite adjacent to the "cellular siliceous rocks." It is desirable to divide this into two groups:

an upper group of very siliceous dolomites, rather finely stratified and called "laminated siliceous rocks" (R.S.F.), and a lower group of ribbon dolomites, more or less chloritic, improperly called "stratified argillo-talcose rocks" (R.A.T. strat.), because of the character of the superficial alteration in place.

The total thickness of this group of dolomites varies from 7.70 m to 9.90 m, with an exceptional maximum of 12.85 m. The thickness of the laminated siliceous rocks alone is rather variable, being between 4.35 m and 6.45 m, with an exceptional maximum of 8.70 m. The thickness of the lower group is more constant, and lies between 3.35 and 3.70 m, with an exceptional minimum of 2.40 m.

In detail, each of the above groups of dolomites may be subdivided into several horizons, which persist throughout the deposit and which succeed each other, from top to bottom, as follows:

	Normal thickness
Upper Group (Laminated siliceous rocks)	
F2b—Dolomitic and micaceous siliceous shales, laminated	1.40 to 3.30 m
F2a—Microgranular siliceous dolomites, with irregular interstratified bands of shale	0.40 to 2.00 m
F1—Microgranular siliceous dolomites, ribboned, with micaceous shales; in places, cherts at the base (F1X)	0.50 to 1.75 m
Lower Group (argillo-talcose rock stratified)	
R5—Chloritic and dolomitic shale, ribboned, generally blackish, containing small interstratified dolomitic layers	0.20 to 0.70 m
R4—Microgranular dolomites, interbedded with dolomitic or chert nodules; in places small interstratified dolomitic chert layers	0.70 to 2.00 m
R3—Chloritic dolomitic shale (similar to R5, but generally more dolomitic)	0.25 to 0.55 m
R2—Microgranular dolomites, generally massive, of light color, with siliceous crystalloblasts; in places chert bands (R2X)	0.55 to 1.45 m
R1—Generally crystalline dolomites, more or less well stratified, in places chert bands (R1x)	0.30 to 0.80 m

The thickness of the individual members is subject to wider variation than that of the group.

Each of the groups are described separately below.

F2b Horizon: Laminated Dolomitic Siliceous Shales (Figs. 3, 4, 5).—This horizon consists essentially of alternating bands of micaceous shales and of microgranular quartz, 0.25 mm in thickness, generally undulating, and commonly showing a large number of minute folds.

The schist bands contain as essential elements dolomite in grains of 5 to 50 mu, chlorite, muscovite flakes that may reach a size of 0.1 mm, angulated quartz grains of 75 mu, and as accessory minerals rutile and detrital zircon. The microgranular quartz bands consist of an allotriomorphic aggregate of quartz grains, in size about 150 mu. In addition, there are also bands of cryptomorphic silica, in part finely dolomitic and packed with submicroscopic inclusions, giving a dirty gray appearance to the thin section in transmitted light. Finally the rock is filled with crystalloblasts of dolomite of 50 mu and more, which may overlap the limits between successive bands. These crystalloblasts are obvi-

ously in the process of being replaced by cryptomorphic or phaneromorphic silica.

The sulfides are present within or on the border of the mica bands as areas having a serrated contour, elongated along the stratification, that may reach a length of 1 mm; within granular quartz bands the sulfides are in two distinct forms, in grains of 0.25 mm maximum, commonly xenomorphic with respect to the quartz grains surrounding them, and in small inclusions of polyhedral form within the quartz grains. The interpretation of these relations will be discussed on a later page.

F2a Horizon: Dolomites with Micaceous Shale Bands (*Figs. 6, 7*).—This horizon has the same structure and texture as the F2b siliceous shales, and actually forms the same unit with them, but the micaceous shale layers are more widely separated from each other, and the rock is less siliceous and more dolomitic. Actually, the microgranular quartz bands of the F2b shales become gradually thicker until they reach 5 mm in the F2a horizon where they become microgranular siliceous dolomites, with grain size, from 8 to 25 mu, isolated or in allotriomorphic aggregates, surrounded by cryptocrystalline silica.

By stages from the F2a dolomites to the F2b siliceous shales, one sees the process of silicification outward from the stratification joints. The microgranular dolomite first undergoes recrystallization, preferably along the joints, resulting in replacement of the small grains by individuals exceeding 0.2 mm which are in turn replaced by an allotriomorphic aggregate of quartz of 0.1 to 0.2 mm grain size. The result of this replacement is two zones parallel to the stratification; one old microgranular dolomitic zone and one, younger, microcrystalline dolomitic quartz zone.

In the microcrystalline dolomitic quartz zones the sulfides are in grains from 0.25 to 0.5 mm, having the contact relations with the quartz as in the F2b horizon; their relations with the dolomite are rather indefinite. In the microgranular dolomitic zones the sulfide occurs as specks of 25 mu maximum and is considerably less abundant.

The micaceous shale bands, of a thickness up to 1 mm, are similar to the corresponding bands of the F2b schists.

F1 Horizon: Ribbon Dolomites with Micaceous Joints (*Figs. 8, 9*).—These dolomites are similar to those of the F2a horizon, but much more regularly stratified, in which the micaceous bands are reduced to less than 0.5 mm in thickness, whereas the dolomitic bands with grain size of 5 to 20 mu enclosed in cryptocrystalline silica represent 25 to 30 percent of the mass.

A microcrystalline silicification occurs in the bands in the form of allotriomorphic quartz areas reaching 0.2 mm, dispersed in the microgranular mass.

The sulfides are in specks of 20 mu associated or not with the microcrystalline quartz.

F1X Horizon: Base Cherts of the "R.S.F." (*Laminated Siliceous Rocks*) (*Fig. 10*).—There are in places at the base of the F1 horizon blackish-gray chert strata. These chert layers are crytomorphic silica filled with submicroscopic inclusions that impart a dirty gray appearance to the thin section in transmitted light. This chert apparently replaces microcrystalline dolomite. It is generally free from mineralization, like the dolomite it replaces.

Where chert is fractured, small areas of phanerocrystalline quartz occur associated with sulfides, or small veins of quartz bordered with sulfides are present. Either the cryptomorphic silica replaced the microcrystalline dolomite, followed by mineralization or the reverse, in the order of silicification, is possible. The absence or scarcity of mineralization in the cherts seemed to indicate that chert silicification was first.

R5 Horizon: Ribboned Chloritic Dolomitic Shales (*Figs. 11, 12*).—The blackish rock is cryptomorphic, partly phyllitic, filled with submicroscopic inclusions, surrounding 5 mu grains of dolomite as well as 10 to 20 percent of angulated quartz grains of from 15 to 20 mu size. There are a few detrital grains of zircon, which indicate the clastic nature of the rock.

The schistosity is emphasized by streaks (up to 0.1 mm) of phyllite oriented parallel to the stratification; this is probably colorless chlorite, of positive optical sign, similar to that shown in the analysis mentioned below. This chlorite could be of dynamometamorphic origin.

The stratification is in places shown by small dolomitic veins of 1 to 2 mm thickness, with granular texture (Fig. 12), or a comb structure (Fig. 16). In these veins the sulfide surrounds the grains of dolomite. There are also sulfides along cleavage planes of the dolomite. These relations indicate that dolomite has been replaced by sulfide.

The horizon is in general much fractured with the filling of the fractures of the same composition and texture as the interstratified veins just described.

In addition to the small veins and fracture filling, the schist is in places strongly impregnated with sulfides in the form of specks of 25 to 100 mu, generally elongated parallel to the schistosity. The dynamometamorphic zones that contain much chlorite and a small amount of dolomite are obviously not as well mineralized as the normal schist.

R4 Horizon: Dolomites with Nodules (*Figs. 13, 14*).—Structurally, this horizon is more or less well stratified dolomite, characterized by quartz or chert nodules.

Texturally, grains of dolomite of from 5 to 10 mu are immersed in the cryptomorphic silica representing 30 to 35 percent of the mass. A quantitative analysis shows that the rock contains more magnesia than required for dolomite, there is a lack of CO_2 to saturate the excess magnesia, and there is present 2.5 to 3% Al_2O_3. The rock must therefore contain chlorite, which in all probability is included in the cryptomorphic silica and merges with it when examined under the microscope.

The nodules, of amygdaloidal shape for the larger individuals (2 to 3 cm along the longer axis), and almost spherical or ellipsoidal for the smaller individuals (0.5 to 1 cm), consist of a nucleus of macrocrystalline dolomite, in allotriomorphic grains of ¼ to ½ mm, containing a multitude of submicroscopic inclusions, and a cortical layer, comparatively clear, composed of dolomite and quartz, in allotriomorphic grains slightly smaller than those of the nucleus, but there are no clear boundaries between the cortical crystallization and the nuclear. The dolomitic cortical layer, is more or less completely replaced by sulfide, while the nucleus remains practically without mineralization. There is no definite indication as to the origin of these nodules.

The stratification of the rock is evidenced by subparallel lenticular layers of 0.3 to 0.6 mm in width, consisting of subidiomorphic dolomite of 150 mu, of replacement quartz, and of sulfides in grains elongated in the plane of the layers.

Some nodules are largely replaced by dark chert. The chert replacement has been from the periphery towards the center, with some centers unreplaced. As in the dolomitic nodules, the mineralization of chert nodules is limited to the cortical layer, and it is hardly possible to determine precisely the time of chertification with respect to mineralization.

The horizon of nodular dolomites shows some peculiar characteristics, such as small interstratified dolomitic veins, or abnormally high silicification.

R3 Horizon: Chloritic Dolomitic Shales (*Fig. 15*).—This horizon is lithologically similar to that of R5, except that the latter is generally more dolomitic. It also shows the same structural peculiarities and the same type of mineralization.

R2 Horizon: Dolomites with Siliceous Crystalloblasts (*Fig. 17*).—These are microgranular dolomites of a lighter shade and of more massive structure than the R4 dolomites.

They contain less silica (25 to 30%) and also less alumina (0.5 to 1.5%). As in R4 dolomites, there is an excess of magnesia, but the excess is less. The R2 dolomites, therefore, also contain chlorite, but in a proportion approximately half that of the R4 dolomites.

A remarkable peculiarity of this horizon is the constant presence, especially along the stratification joints, of crystalloblasts that appear in a thin section as small rods of approximately 1.5 mm length, isolated or in interpenetrating groups without definite orientation. These rods appear as a mixture of dolomite, abundant replacement quartz, and some sulfide. We found no traces of the original mineral, the shape of which is probably tabular.

The R2 dolomites also contain, especially towards the base, dolomitic masses that contain chert masses of irregular shape that reach several centimeters in diameter.

The sulfides are in specks of 25 to 50 mu. The horizon is in all places sparsely mineralized.

R1 Horizon: Crystalline Dolomites (*Fig. 18*).—This dolomite, which is generally well stratified, consists of alternate microgranular and macrocrystalline layers. This rock is capable of considerable "plastic" deformation through the rearrangement of the crystalline texture. It has been observed in a thin section that the large areas of dolomite contain many smaller units. The horizon is not very siliceous. Where mineralized, the texture of the sulfides is derived from the texture of the dolomite that they replace.

FORMATIONS SURROUNDING THE DOLOMITES OF THE "SECOND ORE BODY" OF FUNGURUME.

Lower Formation: The So-called "Argillo-Talcose Rocks" (R.A.T.).

The dolomites of the "second ore body" pass downward, almost without transition, into "Argillo-talcose rocks" (R.A.T.). This is a rather homogene-

ous and probably very thick group of "argillaceous," dolomitic and sandy formations, poorly stratified, and generally greatly fractured, giving a breccia of conglomeratic appearance. It is customary to distinguish gray argillo-talcose rocks and lilac argillo-rocks; the gray argillo-talcose rocks are in contact with the dolomites of the "second ore body." The two kinds of argillo-talc rocks are separated by a tectonic breccia of conglomeratic appearance containing fragments of microgranular dolomite of light color. The stratigraphic position of the argillo-rocks is still uncertain.

In Fungurume, the gray argillo-talcose rocks, under the dolomites of the "second ore body," are an arenaceous formation, the strata of which do not exceed 30 cm and then pass rather rapidly into a shale formation and then into the "breccia of the argillo-talcose rock." In places, the breccia comes directly into contact with the dolomites of the "second ore body."

The arenaceous "gray argillo-talcose rock" are in places mineralized. The shaly "gray argillo-talcose rock," the "breccia of the argillo-talcose rock," as well as the "lilac argillo-talcose rock," are barren.

The Arenaceous "Gray Argillo-Talcose Rock" (Figs. 19, 20).—Macroscopically, the rock is a sandstone of average particle size (0.3 mm) unstratified. Most of the particles are angulated quartz of rather uniform dimensions representing 35 percent approximately of the mass. Other constituents, entirely phyllitic, are probably the products of the alteration in situ of another mineral. Finally, there are fragments of a silicified and mineralized rock which are considered as cataclastic products of silicified crystalloblasts, such as those observed in the shaly "gray argillo-talcose rock" mentioned later.

Treatment by acid leaves a residue of heavy minerals representing 0.2 percent by weight of the rock that includes zircon, rutile, and black tourmaline, in detrital grains of 0.1 to 0.2 mm. The prism fragments of the black tourmaline show an increase of colorless tourmaline, of the same optical orientation as the mother tourmaline. It is difficult to decide whether this is a phenomenon due to dynamometamorphism or addition metamorphism.

Some samples of "gray argillo-talcose rocks" contain grains of sagenite, which are obviously the product of the alteration of a titaniferous mineral, no trace of which has been found (ilmenite?).

The matrix of arenaceous "gray argillo-talcose rocks" is a colorless phyllite with or without finely-disseminated dolomite. The phyllite is of low birefringence (about 0.01) and of positive optic sign. An analysis of a sample of non-dolomitic rock shows the composition of a chlorite which is equivalent to a mixture of 45 percent of antigorite molecules ($2H_2O \cdot 3MgO \cdot 2SiO_2$) and 55 percent of amesite molecules ($2H_2O \cdot 2MgO \cdot 2Al_2O_3 \cdot SiO_2$). The phyllites observed (aside from the muscovite micas) in the dolomites of the second ore body show the same optical features as the phyllite that has just been described and are, therefore, in all probability, chlorites of the same composition.

In general, the grains of the sandstone are distributed approximately uniformly in the matrix; however, there is in places a very remarkable structure of tectonic origin, namely a foliation microstructure.

The sulfide mineralization appears in two aspects: as total or partial replacement, or in a system of small lenticular veins oblique to the stratification.

This system represents the system of shear joints which is conjugated with the longitudinal shearing responsible for the foliation microstructure.

The Shaly "Gray Argillo-Talcose Rocks."—The sandstones just described pass abruptly into a rock of finer grain of essentially the same composition and thence into sandy shale with a chlorite matrix of the same nature as that of the sandstone and containing angulated fragments of quartz and, accessorily, black tourmaline, which becomes more and more colorless with decrease in size of fragments, and of zircon. All these elements do not exceed 25 mu.

The shale also contains dolomitic quartz crystalloblasts entirely similar to those described in connection with the R2 horizon.

Upper Formation at the Second Ore Body: The "Cellular Siliceous Rocks."

This is partly organic about 20 m thick, made up largely of algae. It is of notably heterogeneous primary structure. It was subjected to dolomitization, resulting in heterogeneous texture, with development of macro-crystals up to several centimeters across. It is also considerably silicified with preservation of some of the macrostructure. Dissolving of the carbonates, on the surface, leaves cellular siliceous rock. In depth, the formation is massive and especially resistant to shearing.

Microtectonics.

The "second ore body" is located at the base of a "competent" ensemble of formations—properly called "Mine Series"—reaching a thickness of 220 m. It consists of rather large tectonic units, maintaining a comparatively uniform attitude over several hundred meters both horizontally and vertically. The ore body is, therefore, in direct contact with the "incompetent" ensemble of the subadjacent dolomitic argillo-sandstone formations (argillo-talcose rock).

The formations of the second ore body did not in general suffer any strong dislocations, but were affected by internal deformations which were controlled by the nature of the horizons.

A characteristic of these formations is "longitudinal" shearing, or shearing parallel to the stratification or forming a small angle with it.

In the laminated siliceous rocks and particularly in the upper part, this movement results in small faults that overlap one or more bands and also in microundulations and consequent minute folds (Fig. 28). In the lower part of the laminated siliceous rock (horizon F1) as well as in the R5, R4 and R3 horizons, there are numerous separations of bands, some very close to each other (Fig. 29). In other words the longitudinal shears in the upper laminated siliceous rocks are never opened, but in the other horizons they give rise to small filled fissures.

The system of longitudinal shear joints is in places linked with a conjugated system of transverse shear joints, more widely spaced and arranged stepwise. This phenomenon is especially noticeable in the R4 horizon (Fig. 32).

Shearing is general throughout the formations examined, but the deformations due to minute folding are more localized. As already noted, they are in the upper part of the F2 horizon (Fig. 6) where they are accompanied by "plastic" deformations of the individual bands. A similar deformation occurs

in the R1 horizon of the crystalline dolomites. Minute localized folding of the "competent" type affect certain bands or groups of bands in the horizon F1 of the ribbon dolomites (Fig. 9).

Brecciation is rare within the formations of the second ore body. It occurs more commonly in the "cellular siliceous rocks" immediately at their contacts with the "laminated siliceous rocks." The most fractured horizons of the mineralized group are the dolomitic chlorite shales R5 and R3 (Figs. 11, 31). The least deformed horizon is that of the generally more massive dolomites R2; the arenaceous "gray argillo-talcose rocks" yield to shearing stresses, giving rise to a foliated microstructure.

Diagenesis and Metamorphism.

Origin of the Dolomites.—The dolomites show no sign of derivation from limestones. All the carbonates are exclusively dolomite. These dolomites are in all probability of direct sedimentary origin.

The analyses of the R4 and R2 horizons show that these dolomites contain more magnesia than typical dolomite and that the excess of magnesia is due to the presence of chlorites and not of magnesite. Furthermore, the carbonate filling of the small veins consists exclusively of dolomite.

Dolomitic Recrystallization.—Dolomitic recrystallization is chiefly observed in the basic horizon R1 (Fig. 18) and in the dolomitic quartz bands of the upper part of the laminated siliceous rocks (Figs. 4, 7) and it seems to us that the tectonic stresses had a preponderant influence on this phenomenon that does not seem related to silicification. The R1 horizon is, as a matter of fact, the least silicified. It is less easy to evaluate the effect of the mineralizing solutions on recrystallization.

It seems that the chlorites, and perhaps in general the phyllites uniformly distributed in the mass of a microgranular dolomite, prevent recrystallization or render it more difficult. The dolomitic shale bands of the laminated siliceous rock and the chloritic dolomites R5, R4, R3 and R2 have retained their microgranular texture even where strongly mineralized, silicified, or deformed.

It should be noted, finally, that the dolomites which have suffered recrystallization are "plastically deformed," in undulations or small folds. These "plastic" deformations are also in the dolomitic shale bands of the laminated siliceous rocks (Fig. 6) and more rarely in the chloritic dolomitic shales R5.

Going back to the microtectonics, one might ask why the chloritic dolomites R4 and R2, and even the more schistose horizons R5 and R3, are so rigid that they are deformed most commonly by shearing. It is believed that it is due to their high content of cryptomorphic silica uniformly distributed throughout the mass as a matrix.

Origin of the Chlorite.—It has been noted that the colorless phyllite of low birefringence in the "second ore body" is a very low aluminum chlorite, having indices of about 1.59. The composition is a mixture of 45 percent of antigorite molecules and 55 percent of amesite molecules.

The structure of the chloritic bands in the R5 and R3 horizons leads us to believe that it is of dynamometamorphic origin. It may have been formed at

the expense of the dolomite proper, combining with argillaceous minerals contained in the dolomite. If so, its formation preceded the dolomitic recrystallization referred to in the foregoing section since the presence of the chlorite would appear incompatible with this last phenomenon (under the physicochemical conditions peculiar to the formation studied here).

Silicification.—Silicification is present in three distinct forms: (a) a cryptomorphic, limpid form constituting the matrix of all the dolomites and dolomitic shales; (b) a massive chert, containing sub-microscopic inclusions that impart a gray color in transmitted light; this form is localized and poor in mineralization; (c) a phaneromorphic form in all places associated with macrocrystalline dolomite (and not with microgranular dolomite) and invariably accompanied by sulfide inclusions.

When one considers the total silica content (see Table 1, the distribution of the silica), or the last two forms of silicification separately, there appears no relationship between the amount of the silicification and the degree of tectonic deformations. Such a relationship would appear to exist in the laminated siliceous rock in connection with the phaneromorphic silicification, but the R1 base horizon is in all cases barely silicified regardless of its state of deformation. It must be inferred from this that the differences in the silica contents existed prior to the deformations, either during sedimentation or during diagenesis.

The same lack of a direct relationship is present between the silicification and the mineralization, both with regard to the content and to the nature of the latter.

The origin of the cryptomorphic silica diffused in the microgranular dolomites is not clear. It may have been introduced at any stage in the history of the sedimentary formations.

The microscopic examination of the cryptomorphic chert shows that it replaces the dolomite and is epigenetic. The absence of mineralization in the cherts indicates that it was prior to the introduction of the sulfides (Fig. 10).

The phaneromorphic quartz silica replaces macrocrystalline dolomite (Figs. 5, 7, 10). It replaces either recrystallized dolomites or dolomitic fillings of fractures and results—at least in part—from an addition of material and not exclusively from the recrystallization of the pre-existing cryptomorphic silica.

The relationships of the phaneromorphic silica to the sulfides are variable. Xenomorphic forms of sulfides with the idiomorphic quartz (Figs. 5, 11) in-

TABLE 1

SILICA CONTENTS

Horizons	Residue after attack by HCl, representing approximately the contents of free silica
	%
F2b	74 to 60
F2a	60 to 41
F1	30 to 24
R5	53
R4	33
R3	38
R2	27 to 40
R1	17

dicate that the mineralization was later, but the numerous inclusions of sulfide in the quartz (Figs. 5, 6, 10, 11) indicate earlier simultaneous mineralization. We conclude that the two overlap and that there exists between them a certain genetic bond, but we do not dare to state that the mineralization has been brought about by siliceous solutions, inasmuch as there exists in details a certain independence between the silicification and the mineralization, both quantitatively and locally.

Mineralization.

There are only two metals other than iron represented in the mineralization: copper (associated or not with iron) and cobalt. Copper is always predominant; cobalt never exceeds 1/10 the amount of copper and may be present only in traces.

Copper.

Nature and Bathymetric Distribution of the Mineralization.—In depth the ore is disseminated sulfide grains of the same size as the particle size of the rock, namely 0.5 mm maximum. Certain mineralized horizons are intersected by small quartz-dolomitic veins that are longitudinal or transverse with respect to the stratification and contain sulfide grains of the same size as the grains of the gangue. A continuous filling of sulfides in the small veins is rare.

Most of the data are obtained from drill holes that reach a depth of 400 m, although one hole encountered the ore body at 990 m. The development shows a surficial oxidized zone of green salts (malachite and copper silicates) to a depth up to 100 m, followed by a zone of mixed ore (chalcocite and green salts) to 250 m, and finally an exclusively sulfide deep zone of chalcocite and bornite. The limits of the zones are far from constant. They vary between different deposits and within the same ore body. Horizons completely oxidized adjoin other horizons that are exclusively sulfide. The lower limit of oxidation is only slightly related to the present water table and shows no relationship to a former water table. Signs of oxidation to limonite and development of native copper were observed to the greatest depths reached (990 m) and it seems incredible that the water table could ever have been that low.

Malachite is never observed below 250 m, which would seem to indicate that the descending waters responsible for the oxidation were undersaturated with CO_2 below this depth while retaining their oxidizing power.

The sulfides show no change with depth since the bornite-chalcocite association or chalcocite alone is encountered regardless of depth; thus the ore body intersected at the greatest depth reached consists exclusively of chalcocite.

It might be said that the degree of oxidation of the sulfides and also the degree of sulfide enrichment depends on the present cataclastic state of the mineralized formations. Chalcopyrite is practically absent. Its rare occurrences are in association with bornite and the textural relations of the minerals appear to result from unmixing and not from replacement (Figs. 24, 25). We believe the bornite is a primary sulfide. The chalcocite is generally "white" (in reflected light) above 250 m depth. At 400 m "blue" chalcocite and a little covellite appear. "Blue" chalcocite and covellite seem to be limited to the ore bodies that contain bornite.

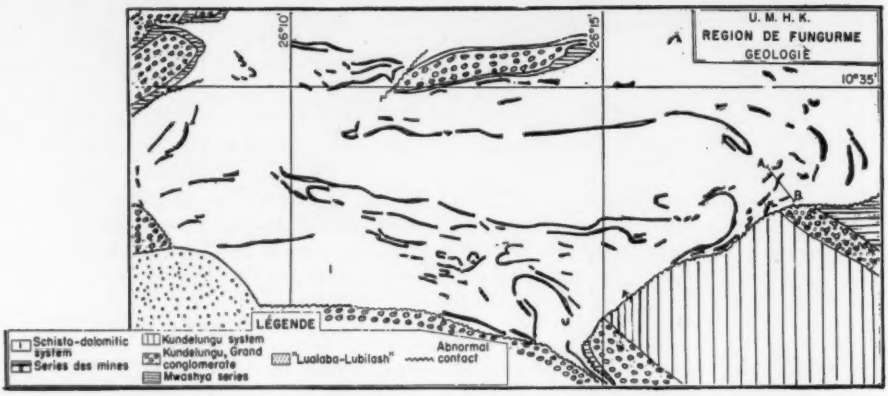


FIG. 1. Scale, 1:100,000.

The relations between bornite and "white" and "blue" chalcocite show three main aspects, which may be present in the same grain:

(a) "Mutual contacts," in which chalcocite may take any form.

(b) A lamellar chalcocite in two or three conjugated systems in bornite, or as vein-like bodies, or even developing along the edges of the bornite grain (Fig. 21). Some of the mutual contact relations appear to be due to the development of the lamellar meshes.

(c) A vein-like penetration of the chalcocite along fissures more or less influenced by the cleavages of the bornite.

Relations (a) and (b) are particularly characteristic of the sulfide grains disseminated in the body of the dolomites while (c) affects the larger grains in the filling of the fractures or in the crust of the nodules of the R4 horizon.

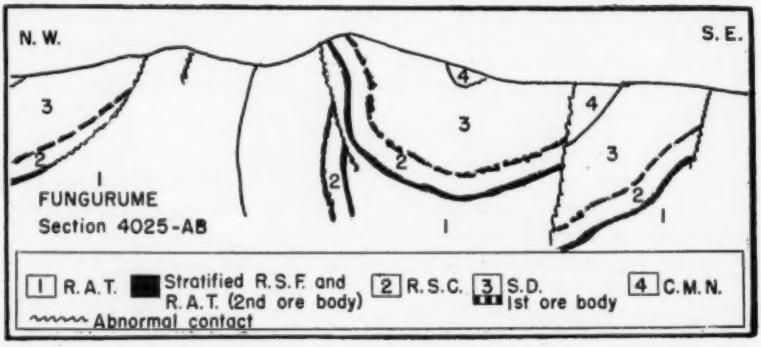
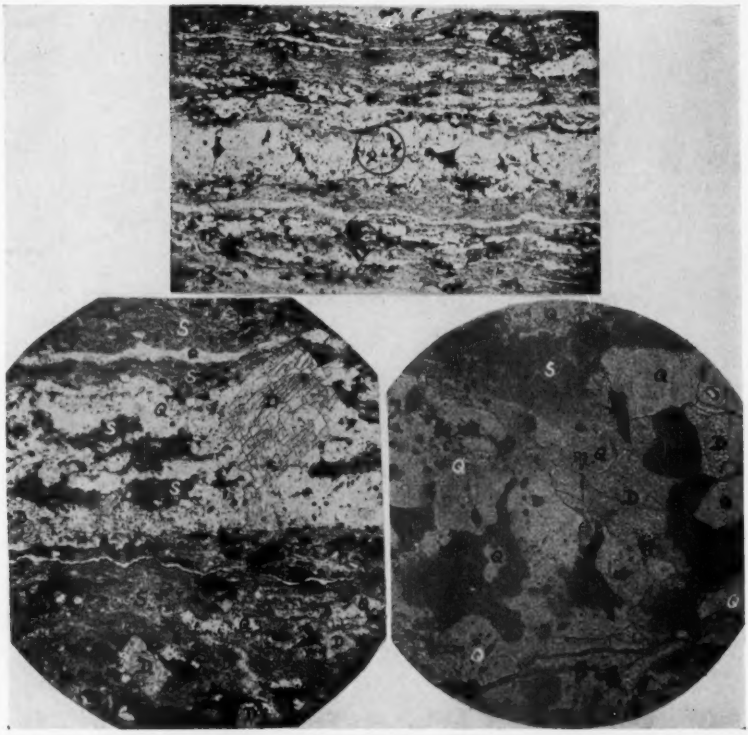


FIG. 2. Scale, 1:5,000.

The vein and marginal arrangements of the chalcocite in the bornite obviously indicate replacement and the irregularity of the distribution of lamellar structures also suggests replacement rather than unmixing. Only the mutual contacts are of rather ambiguous nature.

From the difference in structure of the chalcocite associated with the bornite on fractures (relationship c) and that disseminated within the mineral (re-



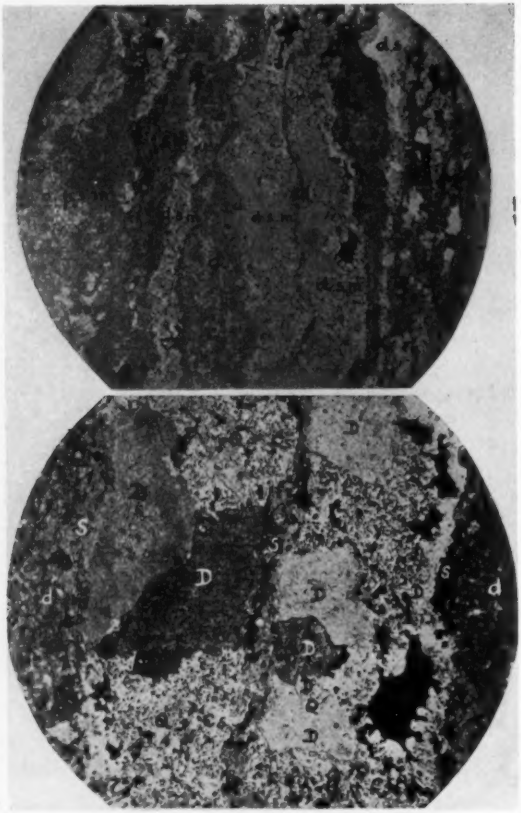
Bore hole No. 104 (-387 m), R.S.F.—Horizon F2b. FIG. 3, × 9. FIG. 4, × 30. FIG. 5 is enlargement of circle in Figure 3. × 85. Q, quartz; S, schist; D, dolomite; black is chalcocite.

lationships a and b) there is no reason to infer a genetic difference; it is due merely to a difference in susceptibility of the bornite grains to deformations, the larger grains being more strongly affected than the smaller grains.

From the above observations it follows: (1) That, in the parts of the deposits where bornite is noted, it is the primary mineral of the second ore body, and (2) that the two varieties of chalcocite result, in most cases, from replace-

ment of the bornite. Some chalcocite may be precipitated directly, but we have no positive evidence of such.

We now come to the question of whether the chalcocite is all of supergene origin or whether some is hypogene. To solve this problem, we refer to the



Bore hole No. 104 (-389.50 m), R.S.F.—Horizon F2a. FIG. 6, × 10. FIG. 7 is enlargement of part of Figure 6. × 30. d, dolomite; s, silicified; ps, partially silicified; Sd, dolomitic schist; m, mineralized; S, schist; Q, quartz; D, dolomite; Cs, chalcocite.

phase diagram of the system Cu_2S–CuS by N. V. Buerger.[1] It may be inferred from this diagram that associations of "blue" chalcocite with "white" chalcocite or covellite may be due to unmixing, and that the chalcocite from which the

[1] Buerger, N. V., The chalcocite problem: ECON. GEOL., vol. 36, no. 1, p. 35, 1941.

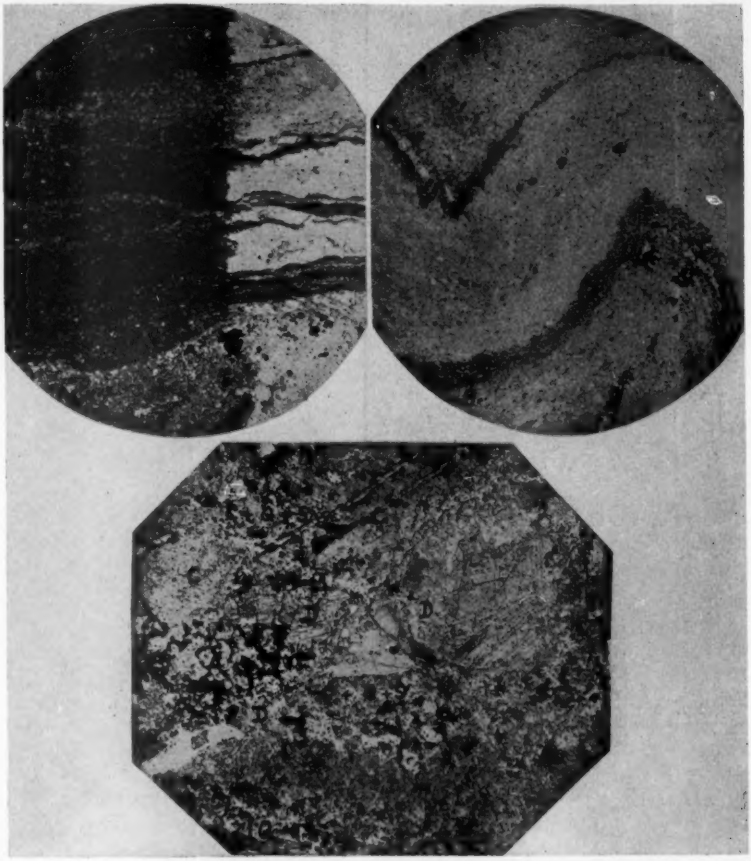


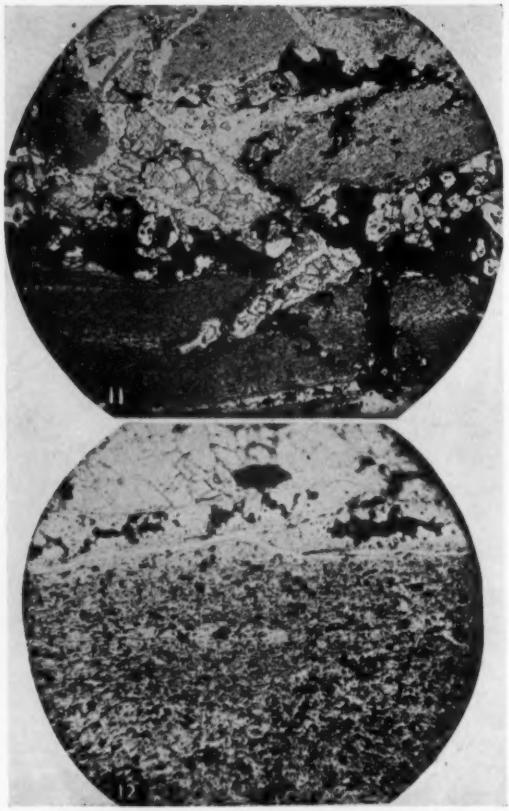
FIG. 8. Horizon F1. Area at right has been etched by HCl to disclose the schistosity of dolomite. × 9.
FIG. 9. Horizon F1, folded. × 9.
FIG. 10. Horizon F1x, brecciated. × 8.5. D, dolomite; C, cherty cryptomorphous zones; Q, quartzy phaneromorphous zones; S, sulfides.

unmixing comes was formed above 78° C and could therefore be hypogene. On the other hand it may be that "white" orthorhombic chalcocite [2] has retained traces of the hexagonal (pseudo-cubic) structure of the high tempera-

[2] We are grateful to Dr. Anton Gray for an X-ray analysis of the chalcocite from drill hole 127 at a depth of 830 m. According to Dr. Anton Gray, the diagram of the powder of this chalcocite is identical to those of the chalcocites of Butte, Montana, and Bisbee, Arizona. These chalcocites are orthorhombic.

ture form of chalcocite (above 105° C). But it is also possible that the apparently cubic residual structure comes from an inherited structure of bornite. Therefore this structure is not conclusive as to the origin.

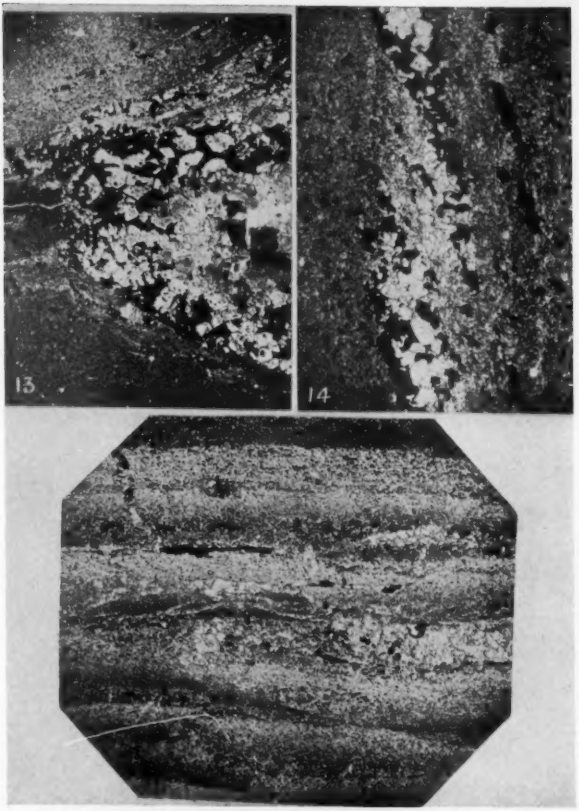
What are the relations between the "blue" and the "white" chalcocite? They are diverse. The two varieties may show a total independence, each having developed on its own within the same grain of bornite; moreover in some grains of bornite only "blue" chalcocite is seen, whereas in others only "white"



Stratified R.A.T.—Horizon R5.

FIG. 11. —Chloritic schist (gray) cut by quartz-dolomite veinlets. Dolomite (light gray) in center of veinlets is replaced by quartz (white) along borders. At right, idiomorphic quartz, with inclusions of chalcocite (black). Large black bands are chalcocite. × 8.

FIG. 12. Schist impregnated with chalcocite (black). Upper part is a dolomitic veinlet, bordered by quartz. × 30.



Bore hole 104—Stratified R.A.T.

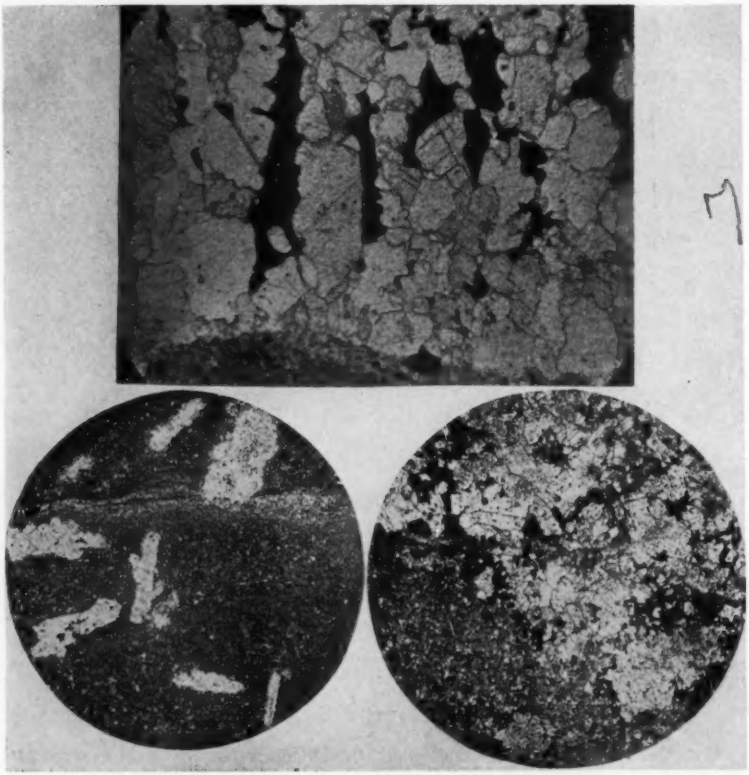
FIG. 13. Horizon R4. Part of a nodule with barren dolomite nucleus and mineralized quartz-dolomite crust. × 9.

FIG. 14. Horizon R4. Mineralized quartz-dolomite stringer with ropy structure. × 28.

FIG. 15. Horizon R3. Alternation of microgranular dolomitic (dark gray) and chloritic (light gray) bands, with more granular vein zones. Black spots are sulfides. × 9.

chalcocite is seen. However, some intimate associations of the two chalcocites occur. Small areas of the blue variety in the center of the white variety, or lamellae of the blue variety, rather differently oriented and developed, on a background of the white variety, or a reticulated development of the two chalcocites in contiguous lamellae (Fig. 22). Although the last two associations mentioned have a rather irregular shape, they may be attributed to unmixing.

Chalcocite-Covellite Association.—This association is rare. Covellite may be present within grains of bornite over small areas, the form of which reflects a clear tendency of the cupric sulfide to develop in lamellae. Several of these small areas within the same grain of bornite tend to be connected. "Blue" chalcocite, which is generally present with covellite, appears to have developed



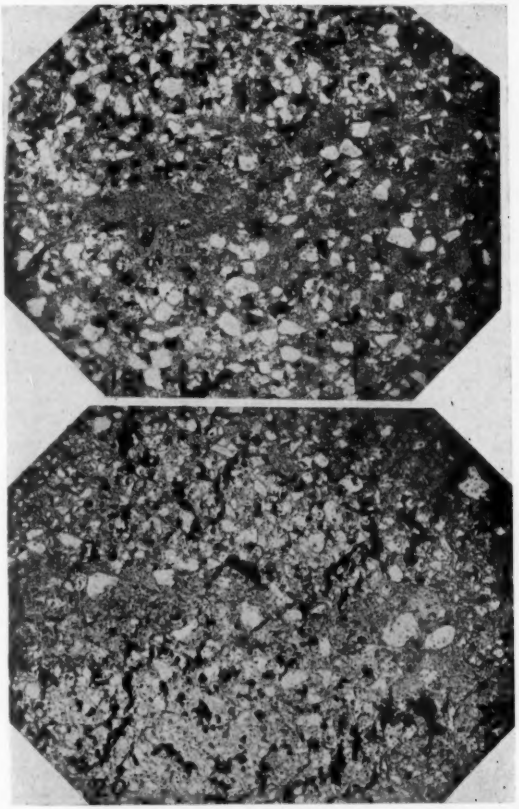
Stratified R.A.T.—Bore hole 104.

FIG. 16. Mineralized dolomitic veinlet, with comb structure. Dolomite (light gray); chalcocite (black). × 32.5.
FIG. 17. Horizon R2. Dolomite with quartz-dolomite crystalloblasts. × 8.5.
FIG. 18. Horizon R1. Dolomite partially recrystallized and mineralized. × 9.

independent of the covellite (Fig. 23). No relation of the minerals suggests unmixing, and where in contact replacement of one by the other is not evident.

In certain grains of bornite there are small areas of a vermicular or granulated aggregate, the mineralogical nature of which has not been determined. These inclusions are always surrounded by covellite.

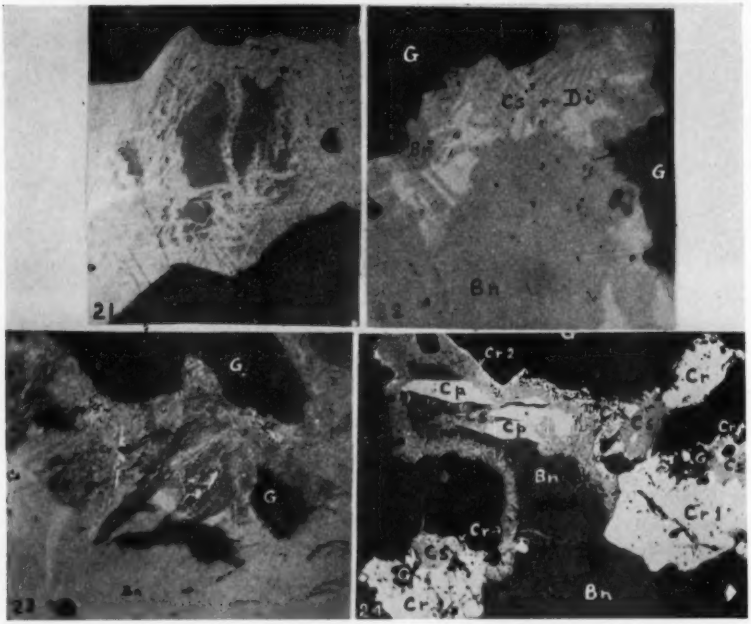
"White" Chalcocite.—"White" chalcocite treated with nitric acid develops two types of structure: a simple lamellar structure (orthorhombic structure of Schneiderhöhn) and a "triangular" reticulated lamellar structure (lamellar structure of Schneiderhöhn). Two effects are to be observed: fractures and striations. The striations show the structure of the mineral whereas the fractures show the structure and/or the texture. The reticulated lamellar structure characterizes the grains consisting exclusively of chalcocite and, curious to relate, it is rare to be able to show it by acid attack in mixed chalcocite-bornite grains in which a reticulated lamellar arrangement of the chalcocite is apparent before the attack. The chalcocite of mixed grains, regardless of its relations



Gray R.A.T.

FIG. 19. × 10.
FIG. 20. Quartz grains (white); chlorite-dolomite groundmass (gray); chalcocite (black). × 10.

with the bornite, shows an allotriomorphic granitic texture in which the individual grains show, or do not show, a simple lamellar structure upon attack by acid. We have encountered only one typical case of a large area of mixed chalcocite-bornite in which the reticulated structure of attack corresponds to the structure visible prior to the treatment.



Second ore body.

FIG. 21. Replacement of bornite (gray) by chalcocite (white). × 240.

FIG. 22. Replacement of bornite (Bn) by white (Cs) and blue (Di) chalcocite; black is gangue. × 280.

FIG. 23. Development of covellite (Cv) around carrollite (Cr) at expense of bornite (Bn); G, gangue. × 220.

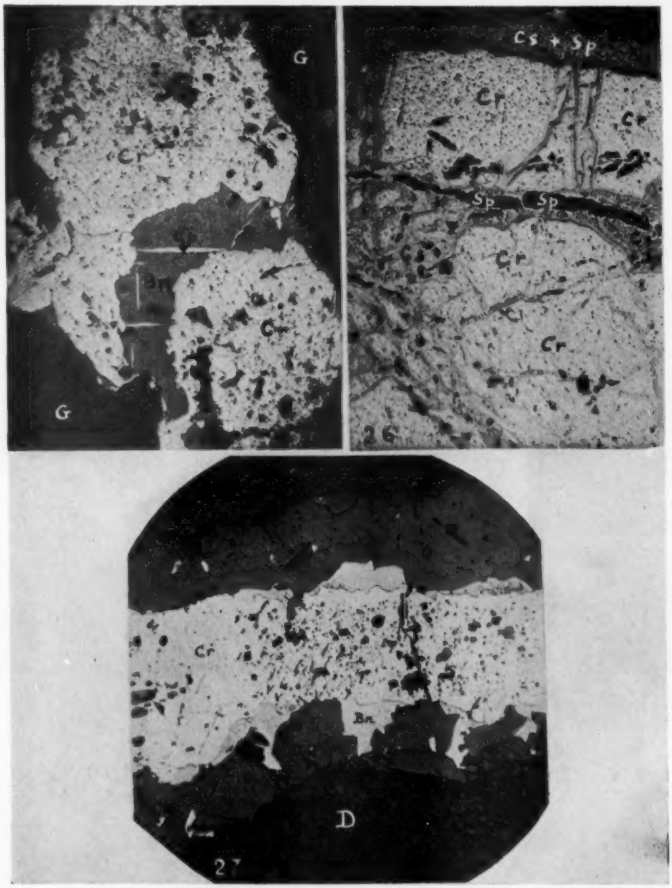
FIG. 24. Replacement of bornite (Bn)-chalcopyrite (Cp) by white chalcocite (Cs), and of latter by secondary carrollite (Cr2). Primary carrollite (Cr1); gangue (G). × 87.5.

The triangular reticulated structure is not revealed at all depths. In a core at 700 m depth with a strong proportion of bornite and blue chalcocite, the white chalcocite developed no reticulated structure, but 30 m lower the chalcocite, entirely white, showed side by side both structures, the simple and the reticulated.

An ore consisting exclusively of white chalcocite at a depth of 250 m, showed only the simple lamellar structure.

These various findings do not appear to us to justify any distinction between chalcocite of hypogene origin and of supergene origin.

It must be expected that any possible hypogene enrichment is superimposed by supergene enrichment until greater depths are reached, since oxidation has



Second ore body.

FIG. 25. Unmixing chalcopyrite (Cp)-bornite (Bn). Carrollite (Cr); gangue (G). × 27.

FIG. 26. Replacement of carrollite (Cr) by chalcocite (Cs) and fixation of cobalt as spherocobaltite (Sp). × 27.

FIG. 27. Relation between carrollite (Cr) and bornite (Bn). Q, quartz; D, siliceous dolomite R.S.F. × 30.

also probably reached these depths. From the different structures conclusions can only be drawn when the conditions of their formation in the districts where the two phenomena of hypogene and supergene enrichment are clearly separated have been studied.

Grade of Ore.—The upper sulfide zone in which the chalcocite dominates contains 6 to 8 percent copper; the surficial oxidation causes the grade to drop on the average to 5.5 to 6 percent. Marked impoverishment appears to start only above a depth of 100 m. With regard to the deep zones in which bornite dominates, information is as yet rather sparse; at 400 m there has been encountered an average of 7 percent copper and at 680 m an average of 5.3 percent.

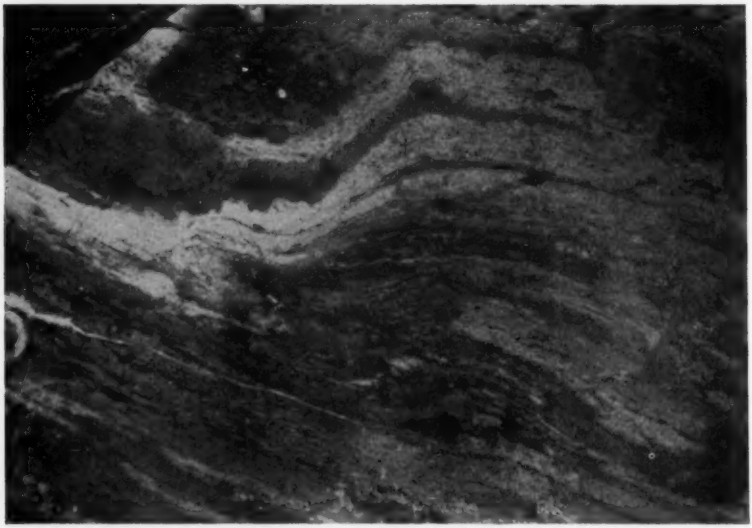
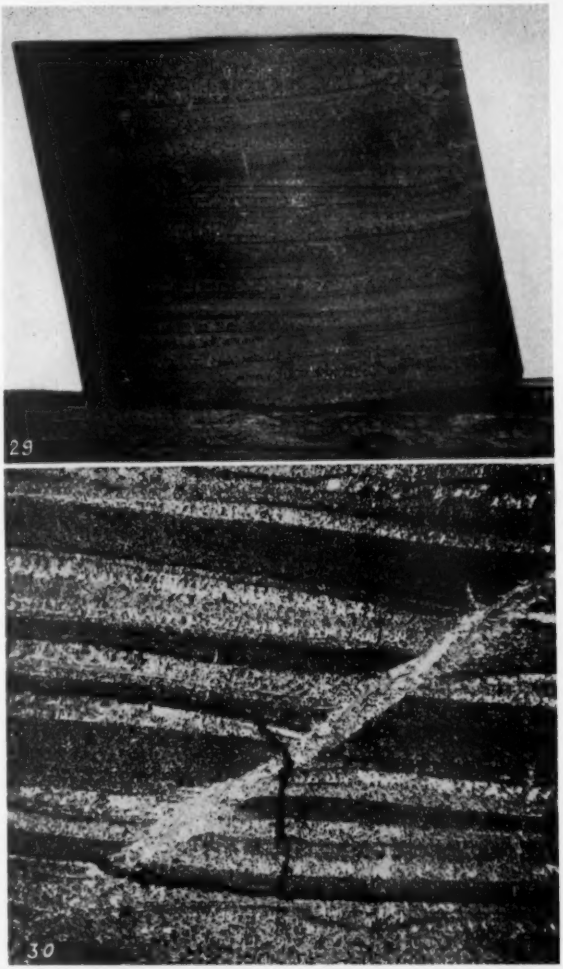


FIG. 28. Second ore body. Typical structure of horizon F2b near contact with the R.S.C. Natural size.

Texture of the Mineralization.—There is in general a correlation between the grain and the texture of the rock and of the sulfides. Where the rock is microgranular, the sulfides are of small grain. Where the rock is coarse the sulfide grains are coarser (Fig. 14); in particular in the small dolomitic veins that have a comb structure, the sulfides are also elongated like the dolomite crystals (Fig. 16). Finally in rock of schistose texture, the sulfides are elongated parallel to the schistosity (Figs. 4, 12). In general this morphologic correspondence suggests either replacement or simultaneous crystallization.

Regarding the crystalline structure we find difficulty in inferring the mechanism of the deposition of the sulfides from the texture of the ore; it is rare to "see" the sulfide replacing the dolomite, for example Fig. 16. Rather one has the impression that the sulfide fills the interstices of the carbonate crystals

leaving its morphologic individuality within the latter (Figs. 4, 11). Where the size of the sulfide areas becomes large, the texture suggests a successive dolomite-sulfide crystallization from a solution. However, this interpretation is obviously extremely improbable.



Stratified R.A.T.—Horizon R4, streaked by veinlets with comb structure and mineralized in chalcocite.

FIG. 29. Drill core. Natural size.

FIG. 30. Polished section. Dolomite (light gray); chalcocite (white). × 2.4.

In the case of schistose bands one may imagine that there was syngenetic replacement of the dolomite grains, or a filling of the intergranular voids created by the tectonic deformations. An unequivocal example of filling of the voids of dynamic origin has been observed in the sandstone "gray argillo-talcose rocks," previously described in detail (Fig. 20).

Stratigraphic Distribution of the Mineralization.—We shall consider here only the sulfide ore bodies.

In the following table are a few typical examples of the stratigraphic distribution of copper content.

TABLE 2

STRATIGRAPHIC DISTRIBUTION OF THE COPPER CONTENTS IN THE "SECOND ORE BODY" OF FUNGURUME

Horizons	1	2	3	4
F2b	5.4	—	5.8	4.7[a]
F2a	5.6	7.0	6.2	7.9
F1	4.5	6.0	4.0	3.8
R5	11.1	14.8	10.2	9.4
R4	6.0	6.8	5.1	4.0
R3	9.0	—[b]	3.6	7.8
R2	2.0	3.8	3.1	1.5
R1	4.3	15.2	—[b]	—[b]

1—Ore body of chalcocite at 100 m depth.
2—Ore body of chalcocite and bornite at 400 m depth.
3—Ore body of bornite and chalcocite at 680 m depth.
4—Ore body of chalcocite at 715 m depth.
[a] Horizon with partial oxidation (limonite).
[b] Horizon not represented.

Horizons F2 and R4, apparently of rather different structures, contain substantially identical sulfide contents.

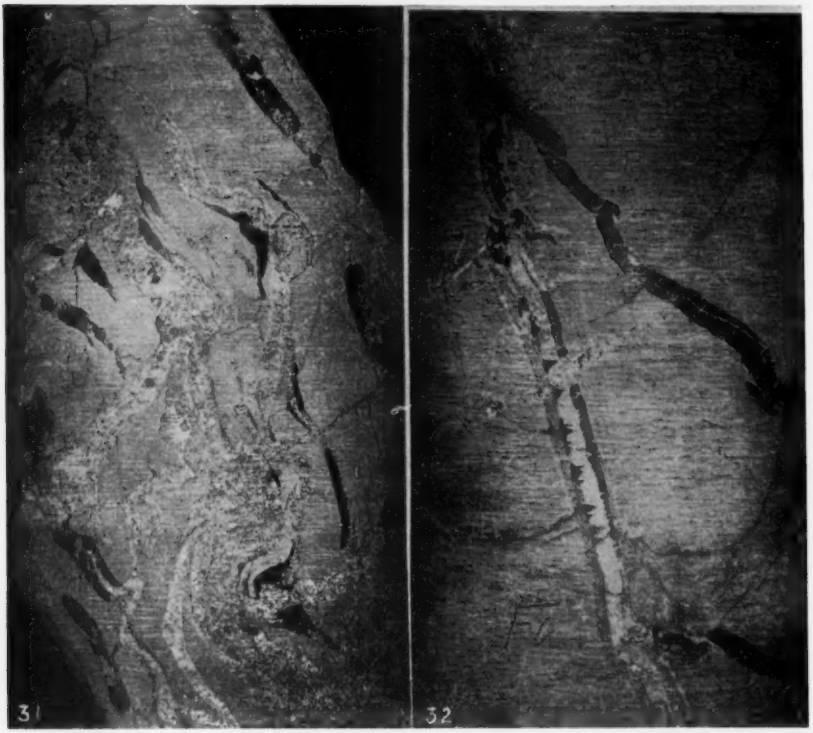
The content of horizon F1 is generally slightly less and the content is clearly less in the R2 dolomites. There is a content peak in the horizon of dolomitic schists R5, which is much fractured and in places a rather high content in the R3 horizon of the same nature as well as in R1 crystalline dolomites where brecciated. The surrounding formations, the cellular siliceous rocks, and the "gray argillo-talcose rocks," are practically barren except along the contacts with the group "stratified argillo-talcose rocks-laminated siliceous rocks." It seems that the tectonic deformations peculiar to each of the horizons of the ore body have played a preponderant part in the distribution of the mineralization.

Theoretically [3] it is seen that the mineralization of any formation is favored to a great extent by the existence of continuous channels of larger dimensions than those of the normal pores of the sedimentary rocks which favor the circulation of the mineralizing solutions (true or colloidal solutions); this "secondary porosity" may be created in the deformations and it is obvious that longitudinal shearing (parallel to the stratification) offers the best chance of creating such channels over long distances. The dimensions of these channels

[3] Rove, Olaf N., Some physical characteristics of certain favorable and unfavorable ore horizons: ECON. GEOL., vol. 42, pp. 57–77, 161–193, 1947.

may remain sub-microscopic but it is necessary that the rock have such a plasticity that the shear surfaces do not close.

Secondly, the pores and channels being granted, the conditions of precipitation or fixing of the ions entrained by the mineralizing solutions must still be set forth. It has been suggested [4] that, all physico-chemical conditions (temperature, pressure, exchange reactions) being favorable, the precipitation will take



Drill cores. Stratified R.A.T. with quartz-dolomite veinlets and chalcocite.
FIG. 31. Horizon R5. Apparent dip of the stratum 60°.
FIG. 32. Horizon R4. Apparent dip of the stratum 75°.

place preferably in media of such semi-permeability that they afford a certain resistance to the passage of the solutions and a selective filtering action with respect to the ions or suspensions (hypo-filtration).

The group of formations of the ore body and the formations which surround it present three types of structure, with a gradation from the point of view of mechanical resistance. On the one side, the "cellular siliceous rocks" with

[4] Mackay, Robert A., The control of impounding structures on ore deposition: ECON. GEOL., vol. 41, pp. 13–46, 1946.

massive structure and coarse and heterogeneous texture do not permit continuous shearing or parallel shearing. The "gray argillo-talcose rocks," as has been seen, are, due to their chloritic composition, eminently plastic rocks in which the longitudinal shearing gives rise to a foliation micro-structure without continuous openings. On the other hand, the intermediate group of stratified argillo-talcose rocks and laminated siliceous rocks presents fine granularity and stratification, and a sufficiently moderate plasticity to permit the development of a network of longitudinal and transverse shear joints sufficiently open for the circulation of the mineralizing solutions, as well as the maintenance of intergranular pores. These characteristics are visible, both macroscopically and microscopically.

The quantitative chemical analysis gives further interesting information.

The analysis of the R4 and R2 horizons show:

1. That these rocks must contain a certain proportion of magnesia in the form of chlorite (though discernable only with difficulty by microscopical examination) of the order of 8 percent in the R4 horizon and 2 to 4 percent in the R2 horizon.
2. That the chlorite content is in direct ratio to the copper content.

Whatever the origin of this chlorite, one can imagine either that it exerts a chemical influence on the precipitation of the sulfides or that it conditions the mechanical deformations. In accordance with the second hypothesis, there may be an optimum chlorite content below which the joints and the pores form more difficultly due to excessive resistance of the rock and beyond which the continuous joints cannot be maintained due to an excess of plasticity.

The probability of such a relationship is strengthened by the high contents of the R5 and R3 chloritic, dolomitic shales in disseminated sulfides. They appear to yield to shearing more easily than the other horizons but are not plastic enough to assure a compact readjustment of the dislocated parts. The semi-permeability necessary for the precipitation of the sulfides might subsequently have been realized after the cementing of the fissures by the dolomitic deposits.

Cobalt.

The cobalt mineralization is generally not as great as that of copper and does not exceed 0.4 percent. It is in the form of carrollite, spherocobaltite and black oxides.

The carrollite is present either in idiomorphic crystals of 1 to 3 mm or in elongated areas following the stratification, which may reach a length of 1 cm. The bornite, which generally accompanies the carrollite, is present on marginal, irregular, and discontinuous areas and in places at depth. The mutual contacts leave doubt as to the paragenesis of the two sulfides but certain forms suggest the replacement of the carrollite by the bornite rather than the reverse. Some bornite associated with the carrollite contains chalcopyrite as lamellar, cuniform, or fusiform type and some in a triangular latticed form, which suggests unmixing and not replacement.

The distribution of the carrollite in the several horizons is independent of the distribution of chalcocite and of bornite. No correlation with the nature of the stratigraphic horizons of the ore bodies is recognized.

An interesting relation is the replacement of the carrollite by "white" chalcocite. Pseudomorphs of chalcocite after idiomorphic forms of carrollite occur in zones at slight depth; this is readily seen in the R2 horizon where the carrollite crystals reach their largest dimensions. The polished sections show the replacement of carrollite by chalcocite along the carrollite cleavages (Fig. 26).

In ore containing bornite that is being replaced by chalcocite, the carollite is generally not attacked (Fig. 24). From this one might conclude that the replacement of carrollite by chalcocite is a supergene phenomenon and that the copper sulfide is more readily replaced than the cobalt sulfide. We have tried to produce experimental replacement of carrollite by immersing it in concentrated and reducing copper solutions. Although substitution is rapidly obtained with bornite, we got no significant results with carrollite.

GENERAL CONCLUSIONS—ORIGIN OF THE MINERALIZATION.

From the evidence stated it seems to follow that the mineralization is epigenetic. However, there are certain arguments favoring a syngenetic, i.e., sedimentary origin. These arguments are:

1. The stratified structure of the deposits.
2. The non-discovery of channels of access for the mineralization outside of the mineralized places.
3. The absence of mineralization in certain favorable formations, namely, the breccia form argillo-talcose rocks of R.A.T.
4. The uniformity in the nature of the mineralization and the constancy of the contents over long, horizontal and vertical range.
5. The disseminated texture of a part of the mineralization; it is understood that this argument, considered alone, is of no value.

Summarizing the arguments in favor of the epigenetic origin are:

1. The vein-like nature of a part of the mineralization.
2. The almost certain epigenetic texture of the mineralization. We say "almost certain" in order to take into account the remark made in the section on the textural relationships, namely that it is rare to "see" the sulfide replace the dolomite. There are indications that silicification and mineralization were simultaneous, and silicification is clearly subsequent to the dolomitic recrystallization.
3. The high temperature of formation of the bornite indicated a bornite-chalcopyrite unmixing structure.
4. The non-existence or slight indication of cataclastic deformation subsequent to the mineralization, which seems to show that the latter took place after or towards the end of the tectonic deformations.
5. The localization of the mineralization in the places that appear "favorable," namely in a group of semi-competent formations adjoining a competent formation (the cellular siliceous rocks).
6. Finally, the relationships of the mineralization to the major tectonic events. However, we shall not dwell on this argument, which is based on the regional tectonics.

In weighing these various arguments, it may be reasoned as follows:

(a) The absence of mineralization in the breccia of argillo-talcose rock, which appears favorable, the uniformity of the mineralization which seems to indicate a horizontal rather than vertical deposition of the ore, and, to a lesser extent, the non-discovery of access channels, seem to us good reasons to consider the introduction of mineralization as subsequent to the breaking up of the mine series into foliations. The seemingly late arrangement in position should be explained by a restarting of the sulfides into motion (resolution) during deformations. This indicates either a syngenetic origin, or an early epigenetic origin of the mineralization.

(b) In favor of the epigenetic hypothesis, mineralized formations are favorable formations and the structure and texture of these layers suggest that they were, at the beginning of the deformations, the most favorable of all those in the lower part of "dolomitic shales series."

None of the arguments in favor of the syngenetic origin can be considered as final, and all of them can be applied to the early epigenetic hypothesis.

We therefore consider the following series of events as the most probable:

1. Diagenetic (cryptomorphic) silicification of the dolomites.
2. Beginning of deformation (folding); the stratified argillo-talcose-laminated siliceous-rock group is developed into horizons favorable to the introduction of mineralizing solutions; mineralization of these horizons, which are perhaps then at a depth of 4 km; the physico-chemical rearrangement due to the mineralization may have resulted in rendering the layers it impregnated more competent than some lower formations, namely the argillo-talcose rock formations.
3. Repeated deformations; breaking up of the Mines Series into foliations; favored by some incompetent horizons in the argillo-talcose rock formations in the vicinity of the Mine Series, on the one hand, and some higher incompetent horizons of the Mine Series, on the other hand. Resolution and readjustment of the sulfides within the ore bodies.
4. Oxidation and supergene sulfide enrichment.

ACKNOWLEDGMENTS.

We wish to thank the management of the Union Minière du Haut-Katanga for having been kind enough to authorize the publication of this paper. We also wish to thank Mr. R. du Trieu de Terdonck, consulting geologist of the U.M.H.K., for his backing and for having assisted us with his advice, recommendations and criticisms. We are also grateful to Mr. J. Vaes, head of the laboratory of the U.M.H.K., for having made his experience in petrographic and mineragraphic matters available to us, and to Mr. B. S. Butler, of Tucson, Arizona, for anglocizing and editing the paper.

GEOLOGICAL DEPARTMENT,
UNION MINIÈRE DU HAUT-KATANGA,
JADOTVILLE, BELGIAN CONGO,
May 3, 1950.

SPECTROGRAPHIC STUDY OF PLATINUM AND PALLADIUM IN COMMON SULPHIDES AND ARSENIDES OF THE SUDBURY DISTRICT, ONTARIO.

J. E. HAWLEY, C. L. LEWIS, AND W. J. WARK.

ABSTRACT.

A quantitative spectrographic technique has been developed to determine platinum and palladium in the common sulphides pyrite, pyrrhotite, pentlandite, and chalcopyrite and in mixed arsenides, chiefly niccolite, gersdorffite and maucherite, in ores of the Sudbury district. This involves concentration by fire assaying and mixing resulting beads with gold amalgam.

The results of both qualitative and quantitative spectrographic analyses on various minerals are given and discussed, and the conclusion is reached that most of the platinum and palladium may be present in discrete mineral particles, some of submicroscopic size, in all of these minerals. It is also indicated that a noteworthy amount of the metals has been deposited with the early sulphides and that they are by no means confined to a late, less intense, stage of mineralization.

INTRODUCTION.

PRODUCTION of platinum and palladium from the Sudbury ores yearly amounts to 200,000 to 500,000 ozs per year, yet, save for the occurrence of the platinum arsenide, *sperrylite,* little information is available as to the occurrence of these and other related metals, rhodium, iridium, and ruthenium, in the ores of the district.

The purpose of the present investigation has been to extend our knowledge of the distribution of these metals in the common ore minerals and to ascertain if a spectrographic investigation could be used to advantage in studying this important metallogenic province both laterally and vertically. This paper is a report of progress as much further work remains to be done.

PREVIOUS LITERATURE AND DISCUSSION.

Discussion of the occurrence of the platinum metals in the Sudbury ores is to be found in papers by Dickson (5),[1] Coleman (4), The Ontario Nickel Commission (11), Phemister (10), and Burrows and Rickaby (3).

Coleman (4) deduced that the amount of platinum metals recovered per ton of sulphides was 0.0468 oz in 1902, 0.0323 oz in 1903, and 0.0193 oz in 1904. He records the investigation of Mr. Mickle in 1897 as demonstrating the association of sperrylite with copper rather than nickel ores. Dickson (5), after assaying pure chalcopyrite, pure pyrrhotite, and a mixture of the two, confirmed the presence of precious metals in chalcopyrite with only traces or none

[1] Numbers in parentheses refer to Bibliography at end of paper.

in pyrrhotite, a number of assays of the former yielding over 0.15 oz platinum per ton, and one as much as 0.35 oz. Palladium and other metals were not estimated.

Analyses of sperrylite listed by Coleman show 0.72 percent rhodium and traces of palladium in this mineral.

The Ontario Nickel Commisssion (11) indicates that, due to the difficulties in chemical analyses and in recovery of the platinum group, estimates of amounts of these metals present in the Sudbury ores are probably low. Palladium is noted as occurring in the largest proportion, then platinum, iridium, and rhodium in the order named. Ruthenium and osmium are present but the bulk of the latter is probably not recovered due to volatilization during smelting.

Association of platinum, iridium, and rhodium with copper-rich ores, along with gold and silver, is also noted by the Commission and the suggestion is made that a similar association of palladium in deposits yielding most palladium is due to the occurrence of "an unknown cupriferous palladium mineral rather than to segregation of palladium in copper (chalcopyrite) ores."

Phemister (10) expresses the view, though not too well substantiated, that the precious metals tend "to accompany the more siliceous and therefore presumably the less intense phases of the general mineralization."

Burrows and Rickaby (3) present tables showing ore smelted and platinum metals recovered for the years 1920 to 1934. From these the average yield of platinum metals per ton of ore smelted has been calculated (Table I). As will be seen later, the resulting figures afford an interesting comparison with the amounts detected spectrographically in some of the common sulphides and arsenides of the ores. The figures show increased recovery of platinum metals with increased production of ore and no doubt also indicate more efficient methods being used.

Although rare, crystals of sperrylite may be found embedded in chalcopyrite, because of their fine size, it is possible they may be overlooked and yet occur

TABLE I.

Year	Ore Smelted (Tons)	Platinum Metals (Oz Troy)	Platinum Metals (Oz/ton)
1920	1,087,531	10,056	0.009
1921	393,768	13,418	0.034
1922	314,120	11,788	0.037
1923	1,141,160	15,625	0.014
1924	1,307,694	18,697	0.013
1925	1,258,849	16,980	0.013
1926	1,309,782	19,495	0.015
1927	1,350,214	22,762	0.017
1928	1,476,704	23,539	0.016
1929	2,033,457	29,615	0.015
1930	2,357,154	68,040	0.029
1931	1,689,874	91,643	0.054
1932	793,552	64,897	0.082
1933	1,523,814	55,755	0.037
1934	2,896,959	200,109	0.069

to some extent in pyrrhotite, pentlandite or pyrite. Recent studies by Burr and Peacock (2) indicate the possibility of palladium, which is clearly not associated with the sperrylite, occurring as a palladium bismuthide as well as in other minerals, such as the antimonide, stibiopalladinite, and the sulphide (with Pt and Ni), braggite. On the other hand, even if some of the platinum group are to be accounted for by discrete mineral particles intergrown with the common sulphides and arsenides of the Sudbury ores, the possibility of part of them being present in solid solution with the sulphides or arsenides needs consideration.

METALLIC MINERALS OF THE SUDBURY ORES—SUMMARY.

Metallic minerals in the Sudbury ores consist chiefly of pyrrhotite, pentlandite and chalcopyrite occurring in both massive and disseminated form as described by the Staff of International Nickel Company of Canada Limited (13). In the various ore bodies the Cu:Ni ratio is given as from 1:2 to 3:1 and the pyrrhotite: pentlandite ratio from about 2:1 to 6.6:1.

Other metallics which have been described in these ores by Wandke and Hoffman (15), Lausen (7), Michener (8), and Michener and Yates (9), include magnetite, cubanite, pyrite and marcasite (probably both of two generations), the arsenides: gersdorffite, niccolite, maucherite; the sulphbismuthide, parkerite; and galena, sphalerite and native gold. Michener and Peacock (8) have noted the occurrence of parkerite near the extremities of one of the ore bodies along with galena, native bismuth, bismuthinite, tetradymite, hessite, cubanite, maucherite, niccolite, sperrylite, and gold.

No attempt is made at this time to present a complete paragenesis for the ores since polished sections alone, without field observations, cannot give the complete story of this complex mineral assemblage and it is possible that many of the minerals have been formed at more than one time. Thus, relatively rare pyrite occurs in massive pyrrhotite as cubic and octahedral crystals and in places appears to be early. Some, however, appears to develop at the expense of pyrrhotite or to cut it in (rare) lenses or veinlets. Some is also associated with late faults in which marcasite is also present.

Pyrrhotite and pentlandite are invariably closely associated as various types of micrographic intergrowths, some of which have been described by Hawley, Colgrove and Zurbrigg (6) and by others.

Chalcopyrite in all specimens is clearly later than pyrrhotite and pentlandite, replacing and cutting both. Galena, sphalerite and carbonates clearly postdate massive pyrrhotite and chalcopyrite, cutting through these in distinct veins. Michener and others indicate that some of these at least appear late in age. Polished sections of cubic sperrylite in chalcopyrite (Fig. 1) show edges slightly corroded and pyrrhotite relicts may be seen between the cube and the invading chalcopyrite. In another case (Fig. 3) a corroded relict of a sperrylite cube occurs in massive pentlandite. In Figure 2 chalcopyrite occurs in fractures in sperrylite. Hence sperrylite, according to these examples, is either earlier than or contemporaneous with pyrrhotite. Some has formed before or with the chalcopyrite and according to other writers, some may be

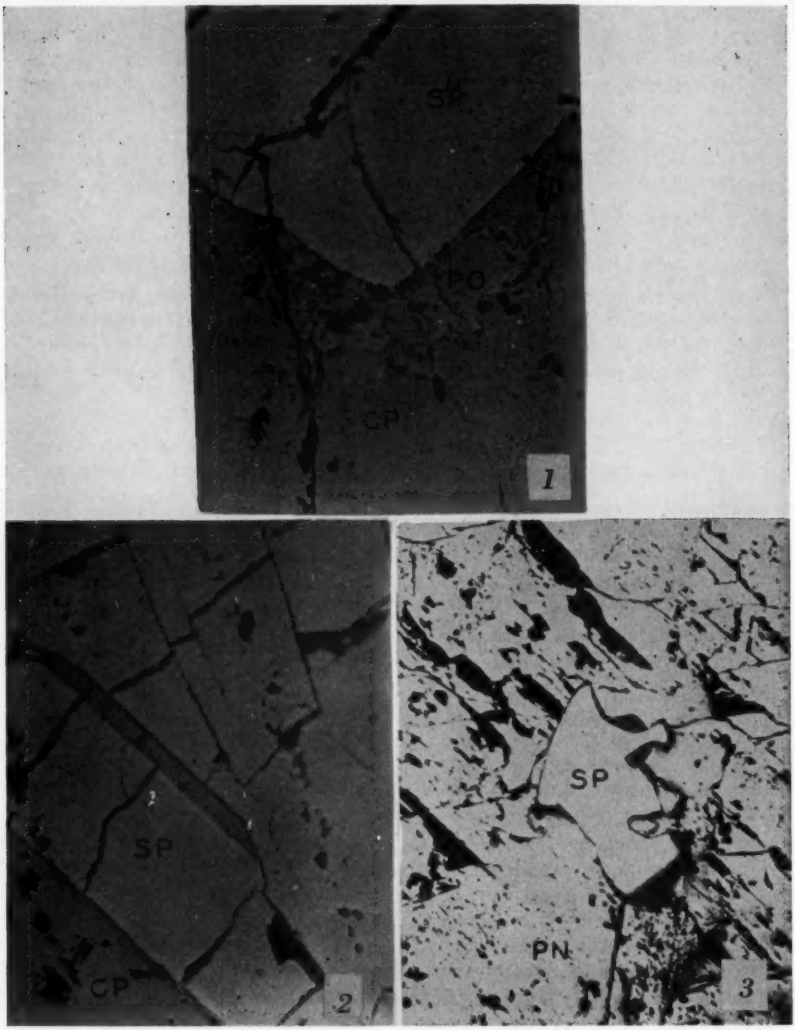


FIG. 1. Sperrylite cube, white, with slightly corroded edges next to pyrrhotite (po) which has been largely replaced by chalcopyrite (cp) × 40 (Spec. S 4).

FIG. 2. Chalcopyrite (cp) filling fractures in sperrylite (sp) × 133 (Spec. S 4).

FIG. 3. Sperrylite (white) distinctly corroded and replaced by pentlandite (pn) × 17 (Spec. Ni 2).

still later. At least it seems fairly certain that all the sperrylite was *not* deposited in the late stages of mineralization. Other arsenides such as gerdorffite, niccolite and maucherite, likewise are in places cut and replaced by chalcopyrite but descriptions of these minerals by Michener also suggest later generations.

QUALITATIVE SPECTROGRAPHIC ANALYSES—SUDBURY METALLIC MINERALS.

Samples of 15 different metallic minerals were carefully picked and purified as far as possible by gravity and magnetic methods and were analyzed with a 2-meter Applied Research Laboratories grating spectrograph under the following conditions:

Grating	: 24,400 lines per inch; dispersion-5.2A per mm. in first order
Electrodes	: Grade I graphite pellets Hemispherical-tipped counter electrodes
Excitation	: 10-ampere d.c. arc at 300 volts
Exposure	: 30 seconds
Slit	: 30 microns
Filters	: 16% transmission
Film	: S. A. No. 2

Table II gives a summary of the elements detected. The constant presence of Co, Ni, Cu, and Ag in all the metallics including oxides is noteworthy. Of the precious metals, platinum was detected in pyrite, pyrrhotite and pentlandite in addition to the arsenide, sperrylite. Palladium appears in these sulphides as well as in the arsenides. Peculiarly, beryllium [2] is present in traces in the nickel arsenides and probably in pyrrhotite and pentlandite. Gold was detectable only in sperrylite, gersdorffite, and niccolite. Antimony and bismuth are present in all palladium-bearing minerals with the exception of chalcopyrite for the former and pyrrhotite and chalcopyrite for the latter. Arsenic, though not highly sensitive spectrographically, was only detected in the arsenides and not in those sulphides carrying platinum or palladium.

Under the excitation conditions and dispersion used none of the sensitive lines of rhodium, iridium, ruthenium or osmium were detectable. This may be due to interference by complex spectra of Co, Ni and Fe as much as to lack of these elements. In a special experiment, cubes of sperrylite were dissolved in a HCl-HNO_3 mixture in a pyrex bomb at 270° C for 20 hours using a technique outlined by Wichers, Schlecht and Gordon [3] of the United States National Bureau of Standards. The reduced metal from the solution was arced in copper electrodes and showed clearly the presence of traces of ruthenium in addition to other elements noted in other samples of sperrylite. It is our experience that ordinary aqua regia treatment of platinum with rhodium and iridium does not always result in solution of the latter elements. Hence concentration of residues of platinum minerals by this means and subsequent spectrographic analysis may be needed to trace down minute amounts of rhodium and iridium.

[2] Beryllium has also been detected in breithauptite (NiSb) and chalcopyrite from Cobalt, Ontario, in this laboratory.

[3] See Nat. Bur. Standards Research Papers 1614 and 1622.

TABLE II.

SUMMARY OF MINOR ELEMENTS IN THE SUDBURY ORE MINERALS.

No. Samp.	Mineral	Formula	Be	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Pd	Ag	Cd	In	Sb	Ba	Pt	Au	Hg	Pb	Bi	Te	Sn
7	Magnetite	Fe_3O_4		X	X	X	X	X	X	X	X				X											
8	Pyrite	FeS_2				X	X	X	X	X	X				X					X			X			
2	Sperrylite*	$PtAs_2$						X		X	X	X	X	X	X	X		X		X	X			X		X
2	Gersdorffite	NiAsS	X	X		X	P		X	X	X		X	X	X			X			P				P	
2	Niccolite	NiAs	X	P		P	P	X	X	X	X		X	X	X			X			X	P			X	
2	Maucherite	Ni_2As_2	X						X	X	X		X	P	X			X				P	P	X		
5	Pyrrhotite	FeS_4	P	X		X	X	X	X	X	X	P		X	X			P		X			X			P
4	Pentlandite	$(Fe,Ni)_9S_8$	P	X			P	X	X	X	X			X	X			P		X			X	P		P
5	Chalcopyrite	$CuFeS_2$		X					X	X	X	X		X	X	P				X			X			X
1	Cubanite	$CuFe_2S_3$		X				X	X	X	X	X			X	P	P		X				P	P		
1	Pyrite (late)	FeS_2		X	P	P	X	X	X	X	X	X			X								X			X
3	Galena	PbS					X	X	P	X	X				X	X		X					X	X	P	X
1	Sphalerite	ZnS			X	X	X	X	X	X	X				X		P		X				X			
1	Specularite	Fe_2O_3			X	X	X	X	X	X	X				X								X			
2	Marcasite	FeS_2		X	X	X	X	X	X	X	X		X		X			X			X					

X—Element definitely present.
P—Element probably present.
* A third sample of sperrylite analyzed after removal of arsenic, by d.c. arc methods, contained a trace of ruthenium in addition to elements reported above.

QUANTITATIVE ANALYSIS OF SULPHIDES AND ARSENIDES FOR PLATINUM AND PALLADIUM.

Various procedures were investigated to determine a satisfactory technique for the quantitative analysis of platinum and palladium in sulphides and arsenides. Since the amounts of these present are very small, the more sensitive but less reproducible d.c. arc method on small samples was not satisfactory. Furthermore, since no analyzed specimens were available to use as standards, a method of preparing suitable standards containing known amounts of the metals had first to be worked out, and treatment of the minerals necessarily had to follow a pattern which would yield similar results.

Both fire assaying and electrolytic methods have been described as suitable for the concentration of platinum group metals from minerals by Azcona and Pardo (1) and Scobie (12). Of these, the fire assay method was developed and modified in such a way as to give a product from which highly reproducible results could be obtained on spectrographic analyses. This method yields much better results than can be obtained directly from gold-platinum metal beads in which some segregation of the metals was found to cause erratic deviations in line intensities.

Preparation of Standards—Gold-Amalgam Method.—The main problem in preparing suitable precious metal standards is to secure a uniformly mixed sample. The preparation of alloys at a low temperature offers the best approach to attain this end.

Experimentation with gold amalgams showed that palladium is sufficiently soluble in these to form a homogeneous alloy and that platinum, though reported as not soluble in mercury, could be mechanically mixed in gold amalgam so as to yield a product giving excellent reproducibility on the spectrograph.

Standards were made up covering the range of concentrations for palladium and platinum occurring in the minerals tested, in the following manner.

Ninety-nine milligrams of powdered gold were accurately weighed and mixed with the least amount of mercury that would allow complete amalgamation. Mixing was done in an agate mortar. When amalgamation was complete, one milligram of palladium was accurately weighed and mixed with the amalgam. This yielded a 1 percent alloy of palladium to 100 of gold plus palladium.

An aliquot of the one percent alloy (in mercury) was further diluted with gold amalgam to obtain a 0.3 percent alloy, and similarly further dilutions with gold amalgam were made to yield 0.1 and 0.03 percent standards.

Separate standards for platinum were made in an identical manner, care being taken to obtain thorough mixing.

Precious metal to mercury ratios in these samples were kept constant at 1:2 in most cases, but experiment showed that even with a 1:3 ratio, the variation in amount of mercury used did not seriously affect the determinations. Gold was used as an internal standard throughout, but mercury if kept at a constant quantity might likewise be used.

Samples of prepared palladium standards were then spread on roughened flat ends of graphite electrodes and analyzed under the following conditions using the low voltage Applied Research Laboratories multisource unit.

Excitation	—Spark Discharge—5 mfd, residual muh, and residual resistance
Gap	—2 mm
Slit	—60 microns
Transmission	—8 percent
Exposure	—15 seconds
Film	—S. A. No. 1

For *platinum* standards, since amounts of this metal in mineral samples were found to be of a low order, more intense, arc-like, excitation conditions were found necessary and the following conditions were accordingly used:

Excitation	—Arc-like—Multi source settings: 45 mfd, 400 muh, 40 ohms
Rotary gap	—30 degrees
Gap	—8 mm (focal plane of gap 3 mm above cathode)
Slit	—60 microns
Transmission	—100 percent
Exposure	—5 seconds
Film	—S. A. No. 1

Film processing conditions:

Develop	—5 minutes
Short Stop Bath	—10 seconds
Fix	—5 minutes
Wash	—10 minutes
Dry	—2½ minutes

Developer changed every four hours.

The following line pairs were used for concentrational ranges shown.

$\frac{\text{Pd } 3489.7}{\text{Au } 3355.1}$	1.0—0.1% Pd
$\frac{\text{Pd } 3460.7}{\text{Au } 3355.1}$	0.3—0.3% Pd
$\frac{\text{Pd } 3404.5}{\text{Au } 3355.1}$	0.1—0.001% Pd
$\frac{\text{Pt } 3064.7}{\text{Au } 2982.1}$	1.0—0.003% Pt

In all cases background corrections were made, and the ratios of intensity of Pd or Pt lines to Au lines were calculated and plotted as ordinates on logarithm paper against percentage of Pd or Pt on abscissae. Examples of working curves obtained are given in Figure 4.

Preparation of Mineral Samples.—Carefully picked samples of pyrrhotite, pentlandite and chalcopyrite, and one of mixed arsenides containing maucherite (Ni_3As_2), niccolite (NiAs) and gersdorffite (NiAsS) were first prepared and purified as far as possible by magnetic or other means. Complete separation of pyrrhotite and pentlandite is not possible due to their fine intergrowths but samples in all cases represent at least 90 percent of the mineral stated.

Samples of one assay ton each were separated into two equal parts and fused in separate crucibles with the following charge:

½ assay ton of mineral
1 assay ton soda
½ assay ton borax
2½ assay ton litharge for pyrrhotite
3 assay ton litharge for chalcopyrite
4 assay ton litharge for pentlandite
Variable KNO_3—adjusted to secure lead button of approx. 25 gms
10 mgs powdered gold (added before fusion or before cupellation)

In some cases it was necessary to resort to scorification in order to obtain a lead button suitable for cupellation. Since copper, nickel and arsenic are exceedingly detrimental to fire-assay fusion, a suitable wet treatment to remove them would be a great help in the process. However, it is probable that any acid used to dissolve these metals would also remove some palladium.

Beads obtained consisted of added gold plus platinum group metals, gold, and silver present in the minerals. These were weighed and then dissolved in test tubes with aqua regia. Solutions were then evaporated, and the residual chlorides redissolved in dilute hydrochloric acid. Sufficient powdered zinc was

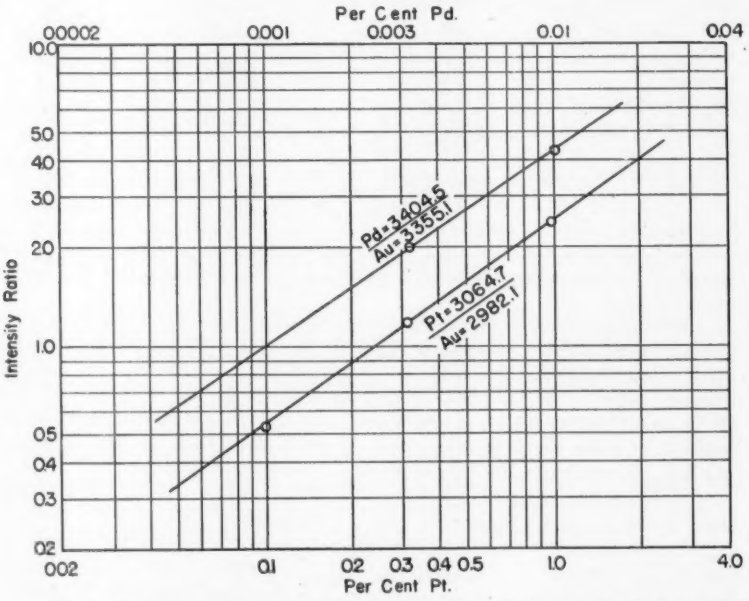


FIG. 4. Working curves for determination of palladium and platinum with gold as an internal standard. Results may be read as percent Pd or Pt of gold alloy, milligrams per assay ton of mineral, or troy ounces per ton of mineral analyzed.

then added to effect reduction of the metals in the "black" form, and dilute HCl added to remove excess zinc. Repeated additions of water, centrifuging and decantation removed excess zinc chloride. After drying, the "black" metals were dissolved in an amalgam of gold and mercury containing 1 part of Au to 2 of Hg; sufficient amalgam being added to bring the total weight of gold plus precious metals of both the original bead and amalgam to 100 milligrams. Samples were then removed from the test tubes and further mixed prior to analysis by the same spectrographic methods used for the standards.

In some cases difficulties were encountered in amalgamation. These were overcome by dissolving the mercury with dilute HNO_3 which converted the gold from the black to the yellow metallic form. After removing the nitric acid solution, washing and drying, the addition of new mercury caused the samples to amalgamate with ease. Absorbed gases (H_2) in the black form of the gold may have hindered amalgamation in these cases. As a result of this, the above procedure was further modified in later work so that the black gold in all cases was converted, by slight heating or standing, to the yellow form.

TABLE III.

PLATINUM-PALLADIUM CONTENT OF SUDBURY MINERALS.

Sample	Mineral	Platinum (Oz/ton)	Palladium (Oz/ton)
S-45	Chalcopyrite	0.045	1.000
S-25	Chalcopyrite	0.110	0.470
S-77	Pentlandite	0.870	0.510
S-70	Pentlandite	1.00+	0.370
S-39	Pyrrhotite	0.455	0.880
S-82	Pyrrhotite	0.105	0.004
S-76	Pyrrhotite	0.005	0.006
S-71	Pyrrhotite	0.025	1.0+
S-79	Pyrite	0.011	0.009
S-41	Mixed Arsenides[1]	Trace	7.223

[1] Mixed arsenides contained maucherite, niccolite, gersdorffite along with some chalcopyrite.

Quantitative determinations of palladium and platinum were then made using spectrographic conditions of analyses identical with those for the standards. Computations were made on the basis of 1 assay ton each and the intensity ratio (PM[4]/Au) results may be read as percent Pt or Pd in gold alloys, as milligrams platinum metals per assay ton, or as troy ounces per ton of mineral, since the standards were made up on the same basis, i.e., of milligrams of platinum metals per 100 mgs of platinum metals plus gold.

Results of Quantitative Analyses.—The results of the analysis of minerals from Sudbury mines are given in Tables III and IV.

The determinations made on five different minerals (Table III) show appreciable but variable amounts of platinum and palladium in all. Lack of more than a trace of platinum in the arsenides but abundant palladium is perhaps surprising. These minerals in addition were clearly rich in gold and silver

[4] PM—Precious metal (Pt or Pd).

since the bead from the concentration of arsenides weighed about five times as much as the average bead from the sulphides.

The presence of about equal amounts of platinum and palladium in pyrite is noted but since this mineral is relatively rare, their importance in this mineral is not quantitatively great.

Pyrrhotites yield some results which are higher in Pd than Pt, a fact which is also borne out by 28 additional analyses of material from Falconbridge Nickel Mines Ltd. All samples of this mineral show at least traces of Pt and Pd. (See Table IV.)

Appreciable amounts of Pt and Pd are also indicated in pentlandite and chalcopyrite and it is clear *that the metals are not all restricted to any one mineral such as chalcopyrite.* Only by further analyses may it be shown that pentlandite is consistently a better host than chalcopyrite for platinum as here indicated.

MODE OF OCCURRENCE OF PLATINUM AND PALLADIUM IN SUDBURY METALLIC MINERALS.

Platinum.—Since the mineral sperrylite has been clearly identified in the Sudbury ores, it would be logical to attribute most of the platinum present in the common sulphides to discrete grains of this mineral intergrown with the sulphides. If this is the case, such grains must be exceedingly fine since they have escaped detection in many polished sections of these ores, examined by the writers. Lack of detectible lines of arsenic in the sulphides carrying platinum may be due more to its insensitivity than absence, and hence may not be significant. The lack of any consistent amount of platinum in 28 pyrrhotites from Falconbridge Nickel Mines Limited, other than traces, suggests that solid solution in pyrrhotite is likely not an important factor in accounting for this metal.

Palladium.—Palladium appears from this study to be most abundant in the mixed arsenides and present in decreasing order in chalcopyrite, pyrrhotite (in which it is erratic), pentlandite, and pyrite. No specific palladium minerals have yet been recorded as present in these ores. The variable results obtained suggest it does occur as a distinct mineral, and, like sperrylite, may be fine-grained as to escape ready detection. The association of Sb and Bi with many minerals carrying palladium suggests one or other of these elements may be combined with it.

Failure to Detect Rhodium, Iridium and Ruthenium.—This study has failed to indicate the presence of rhodium, iridium or ruthenium [5] in any of the minerals studied, due probably both to the low concentrations of these elements in the minerals, compared with platinum and palladium, and in part to the lower sensitivity of two of them under the spectrographic condition used. Possibly concentration of the precious metals by fusing still larger samples would permit their detection. It may well be that these elements are present chiefly in solid solution in any platinum and palladium minerals present.

Pyrrhotites from the Falconbridge Orebody.—A suite of ore specimens was

[5] See detection of ruthenium in sperrylite, p. 153.

collected from locations covering the longitudinal and vertical extent of the ore at Falconbridge Nickel Mine, from surface to the 3,100 level over a length of 4,200 feet, in order to ascertain if any variations in precious metal content could be detected in the common ore minerals. As pyrrhotite with minor pentlandite was the only sulphide common to all specimens, the study was limited to concentrates prepared of this mineral.

Concentration of the samples, assaying, treatment of the beads and amalgamation of reduced precious metals were effected in the manner described above for quantitative analysis.

TABLE IV.

SPECTROGRAPHIC ANALYSES OF FALCONBRIDGE PYRRHOTITES.

Sample	Platinum mgs/assay ton or ozs/ton	Palladium mgs/assay ton or ozs/ton
F–1	0.039	0.003
F–2	0.003	0.003
F–3	0.003	0.005
F–6	0.003	0.004
F–9	0.007	0.145
F–10	0.003	0.002
F–11	0.013	0.008
F–12	0.009	0.004
F–13	1.660	0.210
F–14	0.006	0.001
F–17	0.003	0.0004
F–20	0.013	0.015
F–25	Trace	0.001
F–26	Trace	0.0003
F–30	Trace	0.0004
F–33	0.003	0.008
F–41	0.003	0.009
F–45	0.010	0.013
F–46	0.021	0.009
F–47	0.016	0.011
F–50	Trace	0.005
F–51	0.009	0.003
F–54	0.063	0.014
F–60	0.003	0.0014
F–61	Trace	0.0004
F–62	Trace	0.002
F–64	0.010	0.006
F–65	0.019	0.007

The results are given in Table IV.

Discussion of Results.—Amounts of platinum and palladium determined in 28 pyrrhotite concentrates vary greatly and the amounts of one are not in all cases related to the other.

Eliminating F-13, which gave an unusually high value, and the samples showing only trace amounts, the average of the platinum values is 0.021 mg and of the palladium, 0.008 mg or Troy oz/ton. The very low amounts present in some samples indicate that not more than traces could be present in solid solution and the erratic distribution in others again suggests discrete platinum and palladium minerals may be present and intergrown with the pyrrhotite or pentlandite in a very fine form.

Samples F-60 to F-65 were taken across the width of the orebody. F-64 and F-65, nearest the footwall, show higher values than do F-60 and F-61. Otherwise the results show no particular trend or zoning either vertically or longitudinally. From the practical point of view they do indicate pyrrhotite as a variable host for platinum and palladium.

CONCLUSIONS.

Qualitative and quantitative spectrographic analyses of some of the common metallic sulphides and arsenides of the Sudbury ores show the presence of platinum and palladium in many of these. Beryllium appears to be characteristic of certain arsenides.

The quantitative results indicate that most platinum is associated with pentlandite and most palladium with chalcopyrite and mixed arsenides, and both elements occur in pyrrhotite and pyrite to a lesser extent. Analysis of 28 pyrrhotites from Falconbridge Nickel Mine shows minute quantities of both platinum and palladium in almost every specimen.

The erratic distribution of these metals in the minerals suggests that both are present as finely intergrown minerals of platinum and palladium such as sperrylite and possibly antimonides or bismuthides of palladium, and that only minute amounts may be accounted for by solid solution in the common metallics. Such fine intergrowths (and solid solutions) in the early sulphides, pyrite, pyrrhotite, pentlandite and chalcopyrite, are considered as likely early in age, and it is believed that by no means all of the platinum metals were deposited during the latter, less intense phase of mineralization. This is supported somewhat by the fact that no indication of regular distribution or zoning of the precious metals, which might be expected, if all were late in age, has been found in the Falconbridge type of orebody, but it is admitted the situation may be different in offset types of ore as at the Frood (Yates, 14) where zoning of the sulphides has been indicated. Clearly further investigations are required.

The method of concentrating the platinum metals by fusion and cupellation has been further developed and a new spectrographic technique worked out for the analysis of precious metal beads using gold amalgams. The methods may be applied to other base metal ores to determine their platinum or palladium content.

Similar concentrations but from much larger samples will be needed in order to trace the host minerals for rhodium, iridium, and ruthenium, some or all of which may be found in part in solid solution in the platinum or palladium minerals.

Acknowledgment.—The spectrographic research described in this paper has been made possible by the Research Council of Ontario to whom the writers are indebted for the spectrographic equipment and supplies.

QUEEN'S UNIVERSITY,
KINGSTON, ONTARIO, CANADA,
Nov. 1, 1950.

BIBLIOGRAPHY.

1. Azcona, J. M. L. de, and Pardo, P., Spectrochemical determination of the noble metals in minerals previously concentrated by assay or electrolysis: Spectrochim. Acta, vol. 2, pp. 185–201, 1942.
2. Burr, S. V., and Peacock, M. A., A preliminary study of the alloys of palladium and bismuth: Toronto Univ. Studies, vol. 47, pp. 19–30, 1942.
3. Burrows, A. G., and Rickaby, H. C., Sudbury nickel field restudied: Ontario Dept. Mines Ann. Rept., vol. 43, pt. II, 1934.
4. Coleman, A. P., The Sudbury Nickel Region: Ontario Bur. Mines Ann. Rept., vol. 14, pt. III, 1904.
5. Dickson, C. W., Note on the condition of platinum in the nickel-copper ores from Sudbury: Am. Jour. Sci., vol. 15, pp. 137–139, 1905. Distribution of the platinum metals in sources other than placers: Canadian Min. Inst. Jour., vol. 8, 1903.
6. Hawley, J. E., Colgrove, G. L., and Zurbrigg, H. F., The Fe-Ni-S System: Econ. Geol., vol. 38, pp. 335–388, 1943.
7. Lausen, C., Graphic intergrowth of niccolite and chalcopyrite, Worthington Mine, Sudbury: Econ. Geol., vol. 25, pp. 356–364, 1930.
8. Michener, C. E., and Peacock, M. A., Parkerite from Sudbury, Ontario: Am. Mineralogist, vol. 28, pp. 343–355, 1943.
9. Michener, C. E., and Yates, A. B., Oxidation of primary nickel sulphides: Econ. Geol., vol. 39, pp. 507–514, 1944.
10. Phemister, T. C., Igneous rocks of Sudbury and their relation to ore deposits: Ontario Dept. Mines Ann. Rept., vol. 34, pt. VIII, 1925.
11. Report of the Royal Ontario Nickel Commission, 1917.
12. Scobie, A. G., Spectrographic assay for gold and the platinum metals: Canadian Inst. Min. Metallurgy Trans., vol. 58, pp. 309–322, 1945.
13. Staff—International Nickel Company of Canada Limited, Canadian Mining Mag., vol. 65, no. 5, May 1946.
14. Yates, A. B., *in* Structural Geology of Canadian Ore Deposits—A Symposium: Canadian Inst. Min. Metallurgy, p. 612, 1948.
15. Wandke, A., and Hoffman, R., A Study of the Sudbury ore deposits: Econ. Geol., vol. 19, pp. 169–204, 1924.

PEGMATITES OF THE VAN HORN MOUNTAINS, TEXAS.[1]

PETER T. FLAWN.

ABSTRACT.

Zoned and unzoned perthite-quartz-plagioclase-muscovite pegmatites in the form of tabular bodies, irregular bodies with tabular branches, irregular masses, elongate lenses, *lit-par-lit* zones, and small augen and stringers are distributed throughout the Precambrian metasedimentary rocks of the Mica Mine area, Van Horn Mountains, Texas. Zoned bodies have a core of perthite and quartz and a plagioclase-quartz-perthite-muscovite wall zone. The pegmatites contain numerous schist inclusions, and some show evidence of contamination by biotite schist and amphibolite.

Intimate penetration of the host rock by pegmatite fluids was accomplished by a combination of dilation and digestion. Dilation was effected by injection pressure and (to an unknown degree) orogenic stresses. Crystallization of a solution containing a large excess of potash took place in a closed or restricted system where a delicate balance of solubility factors was maintained for long periods or in a solution of low viscosity, thus facilitating growth of large crystals about a limited number of centers. Zoning and textural relationships are accounted for under these conditions. The importance of horizon and mode of emplacement in the formation of pegmatite textures and shapes is emphasized. A review of the granitization, palingenesis or anatexis, open-system (or aqueous), and magmatic theories of pegmatite origin shows that the features of Mica Mine pegmatites are best explained by the magmatic theory.

The Mica Mine area has possibilities of exploitation for feldspar and scrap mica.

INTRODUCTION.

PRECAMBRIAN metasedimentary rocks intruded by pegmatites are exposed in the Mica Mine area of the Van Horn Mountains (Fig. 1). The area is about 15 miles south-southwest of Van Horn, Texas, and is reached by a county road that turns south from U. S. highway No. 80 within the western limits of Van Horn.

The pegmatites of the Mica Mine area are mentioned in the reports of Von Streeruwitz (26, 27),[2] Baker (4), and Redfield (21), but no systematic investigation of the area was made prior to the present study. In a project by the U. S. Bureau of Mines (11) during World War II an investigation was made of the sheet (strategic) mica deposits of the Mica Mine. The project was confined to exploration, analysis, and metallurgical testing in conjunction with the operations of the Texas Mica and Feldspar Company.

The present study is a project of the Bureau of Economic Geology of The University of Texas.[3] The field work was done during 1949 and 1950. The

[1] This paper is part of a dissertation submitted to Yale University in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

[2] Numbers in parentheses refer to Bibliography at end of paper.

[3] Published by permission of the Director, Bureau of Economic Geology, University of Texas.

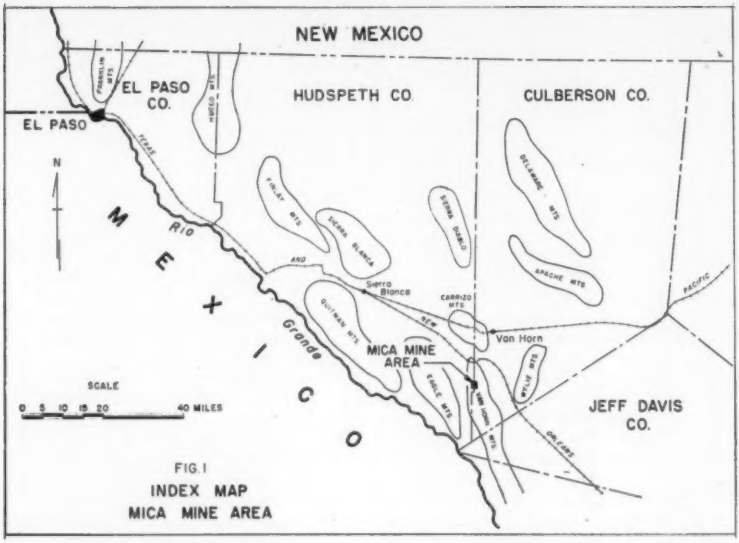


FIG. 1
INDEX MAP
MICA MINE AREA

entire area was mapped by plane table and telescopic alidade on a scale of 200 feet to the inch (Fig. 2). The area around the Mica Mine No. 1 (Fig. 14), from which most of the sheet mica produced to date was recovered, was mapped on a scale of 40 feet to the inch.

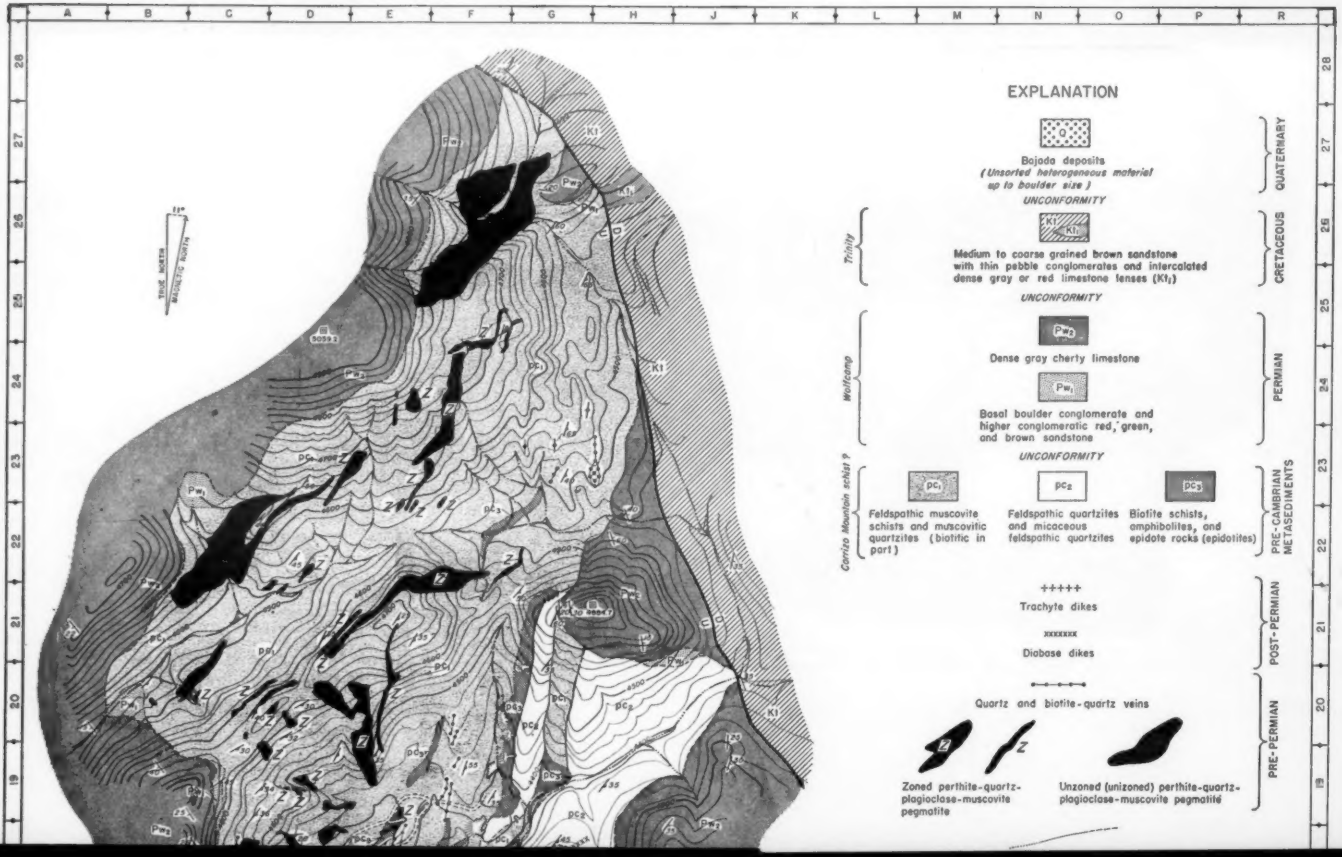
The writer wishes to thank Dr. J. T. Lonsdale and Dr. V. E. Barnes of the Bureau of Economic Geology, Dr. S. E. Clabaugh of The University of Texas, Dr. Adolph Knopf of Yale University, and Dr. L. R. Page of the U. S. Geological Survey, for helpful criticism and advice.

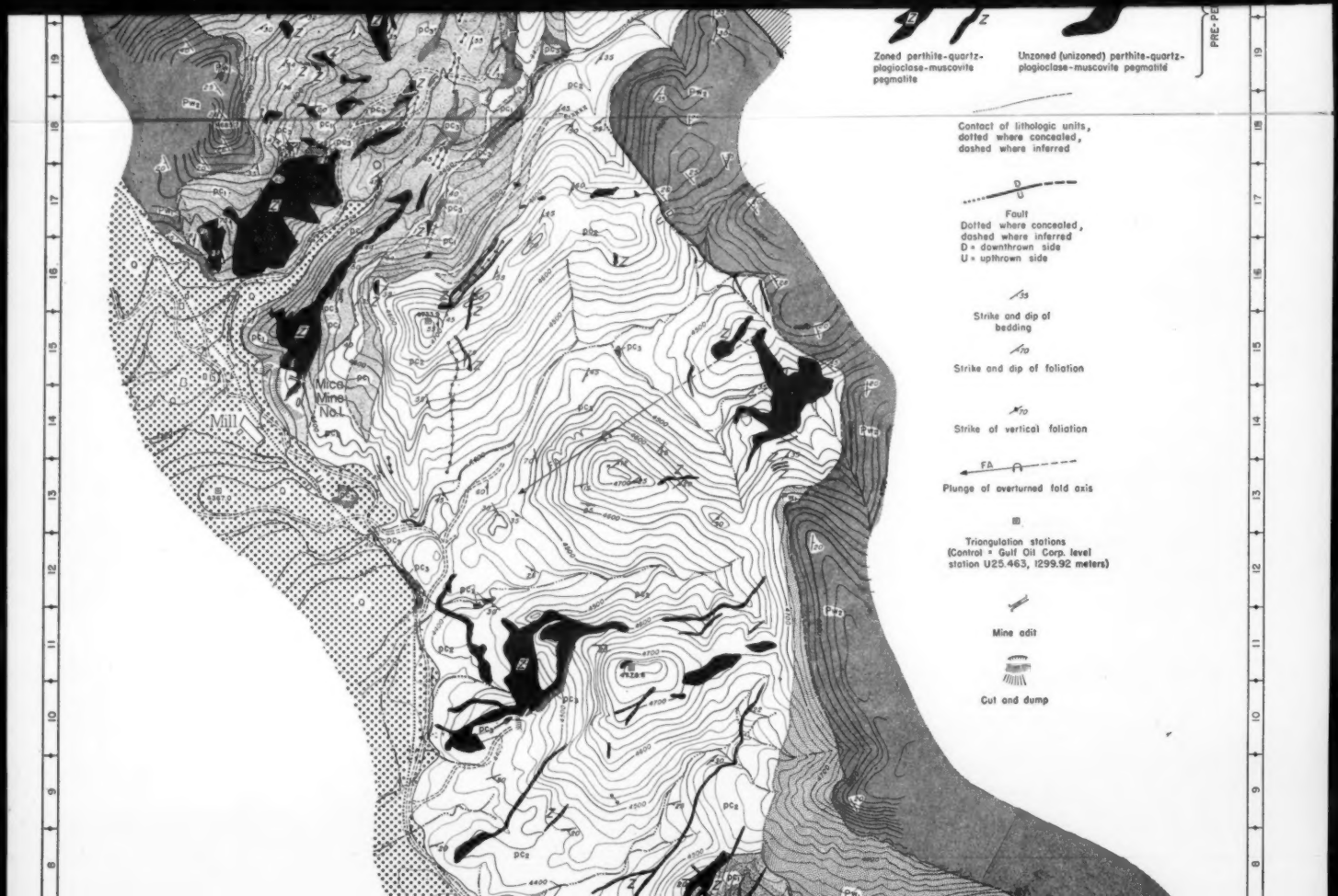
GENERAL GEOLOGY.

The Precambrian rocks of the Mica Mine area are exposed beneath unconformably overlying Permian (Wolfcamp) rocks in a horst that forms the northwest spur of the Van Horn Mountains. The Precambrian and Permian rocks are upthrown relative to Cretaceous rocks (Fig. 2).

Precambrian Rocks.

The Precambrian rocks of the Mica Mine area consist of a thick sequence of feldspathic quartzites and muscovite schists containing thin beds and lenses of biotite schist and amphibolite. The metasedimentary rocks can be grouped into three units: (1) feldspathic muscovite schists and muscovitic quartzites, biotitic in part; (2) feldspathic quartzites and micaceous feldspathic quartzites; and (3) biotite schists and amphibolites. The only difference between the first two units is the mica content. The schists contain quartzite beds of varied


A B C D E F G H J K L M N O P R
18 19 20 21 22 23 24 25 26 27 28
True North
Magnetic North
EXPLANATION
Bajada deposits
(Unsorted heterogeneous material up to boulder size)
QUATERNARY
UNCONFORMITY
Trinity
Medium to coarse grained brown sandstone with thin pebble conglomerates and intercalated dense gray or red limestone lenses (Kt1)
CRETACEOUS
UNCONFORMITY
Wolfcamp
Dense gray cherty limestone
Basal boulder conglomerate and higher conglomeratic red, green, and brown sandstone
PERMIAN
UNCONFORMITY
Carrizo Mountain schist ?
Feldspathic muscovite schists and muscovitic quartzites (biotitic in part)
Feldspathic quartzites and micaceous feldspathic quartzites
Biotite schists, amphibolites, and epidote rocks (epidotites)
PRE-CAMBRIAN METASEDIMENTS
Trachyte dikes
Diabase dikes
POST-PERMIAN
Quartz and biotite-quartz veins
Zoned perthite-quartz-plagioclase-muscovite pegmatite
Unzoned (unizoned) perthite-quartz-plagioclase-muscovite pegmatite
PRE-PERMIAN


Zoned perthite-quartz-plagioclase-muscovite pegmatite
Unzoned (unzoned) perthite-quartz-plagioclase-muscovite pegmatite
PRE-PE
Contact of lithologic units, dotted where concealed, dashed where inferred
Fault
Dotted where concealed, dashed where inferred
D = downthrown side
U = upthrown side
Strike and dip of bedding
Strike and dip of foliation
Strike of vertical foliation
Plunge of overturned fold axis
Triangulation stations
(Control • Gulf Oil Corp. level station U25.463, 1299.92 meters)
Mine adit
Cut and dump
Mica Mine No.1
Mill

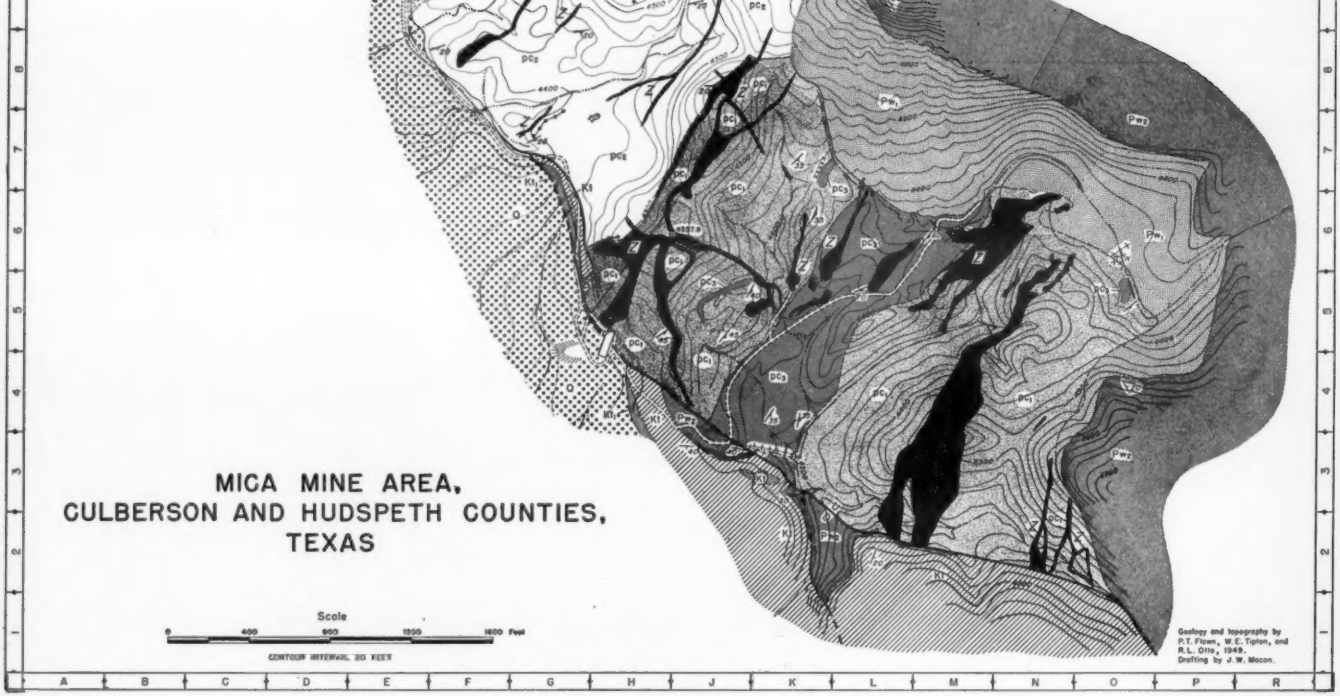

MICA MINE AREA,
CULBERSON AND HUDSPETH COUNTIES,
TEXAS
Scale
0 400 800 1200 1600 Feet
CONTOUR INTERVAL 20 FEET
Geology and topography by
P.T. Flawn, W.E. Tyton, and
R.L. Otto, 1949.
Drafting by J.W. Macon.
A B C D E F G H J K L M N O P R

FIG. 2

thickness and the quartzites contain schistose members. Biotite schist and amphibolite make up less than 10 percent of the sequence.

Structure.

The rocks of the Mica Mine area show a more or less uniform strike and dip without any of the contortion common in Precambrian metasediments. The major structure is an asymmetric fold, the axis of which is shown in Figure 2. Small open folds and local distortions connected with pegmatites are in evidence. The general restriction of the quartz veins to a north-south linear zone indicates an old locus of fissuring.

The foliation shown by symbols on Figure 2 is a bedding-plane foliation. It is expressed by orientation of mica parallel to the planes of contact of major and minor litholigic units, that is, the original stratification of the rocks. In the massive quartzite beds the foliation is difficult to determine megascopically, but in thin section the mica is invariably oriented. In the amphibolites the amphibole may or may not show a lineation. Commonly a mat of non-lineated hornblende needles occurs in the plane of the foliation, giving the rock a gneissic appearance. Locally the more micaceous rocks may show a rucking or even small folds of some inches in diameter.

Petrography of the Quartzite-Muscovite Schist Sequence.

The Quartzites.—Feldspathic metaquartzites with variable content of muscovite and biotite occur throughout the metasedimentary series. They occur as thin beds (up to 3 feet) within the schistose sections and as massive beds (up to 30 feet), separated by thin layers of schist, in the quartzite sections. Quartzites make up 30 to 40 percent of the exposed Precambrian rocks.

TABLE 1.

ESTIMATED MODES (PERCENT BY VOLUME) OF REPRESENTATIVE ROCKS OF THE QUARTZITE-MUSCOVITE SCHIST SEQUENCE.

	I	II	III	IV	V*
Quartz	70	50	64	60	46.2
Microcline	9	37	15	10	31.4
Plagioclase	15	5	15	5	9.7
Muscovite	5	6	—	25	12.7
Biotite	—	2	5	—	—
Magnetite or ilmenite	1	—	1	—	—
Zircon	tr	tr	tr	tr	tr
Totals	100	100	100	100	100.0

* Mode calculated by Rosiwal analysis.

I, Muscovitic feldspathic quartzite; average grain size 0.1 to 0.2 mm (maximum grain size 4 mm).
II, Biotitic-muscovitic feldspathic quartzite; average grain size 0.2 to 0.4 mm.
III, Biotitic feldspathic quartzite; average grain size 0.2 mm.
IV, Muscovite schist; average grain size 0.5 mm.
V, Muscovitic feldspathic quartzite (slightly schistose); grain size 0.2 mm.

TABLE 2.

CHEMICAL ANALYSES OF PEGMATITE AND COUNTRY ROCK, MICA MINE AREA (R. M. WHEELER, ANALYST).

	I	II	III	IV
SiO_2	78.15	77.12	78.37	79.00
Al_2O_3	11.09	13.69	12.57	11.38
Fe_2O_3	1.41*	0.80*	1.52*	0.68*
FeO	nd	nd	nd	nd
MgO	0.25	1.45	0.97	0.25
CaO	0.42	0.37	0.35	0.80
Na_2O	1.64	1.91	1.85	2.45
K_2O	5.56	3.00	3.35	3.45
H_2O-	nd	nd	nd	nd
H_2O+	nd	nd	nd	nd
Ignition loss	0.95	1.38	1.56	1.08
TiO_2	0.11	0.13	0.17	0.14
P_2O_5	0.02	0.02	0.01	—
MnO	0.01	0.02	0.03	nd
CO_2	nd	nd	nd	nd
BaO	nd	nd	nd	nd
Totals	99.61	99.89	100.77	99.23

* Total iron reported as Fe_2O_3.
nd = not determined.

I, Feldspathic (microcline) quartzite, Mica Mine area.
II, Biotitic muscovite schist, Mica Mine area.
III, Muscovite schist, Mica Mine area.
IV, Representative pegmatite, Mica Mine area (30 percent pink microcline perthite, 40 percent white plagioclase, An_7, 20 percent quartz, 10 percent muscovite).

On the weathered surface the rocks are dark brown. A fresh face shows a pink to buff color. The rock is a hard vitreous quartzite in which individual quartz grains can easily be distinguished. The orientation of the mica flakes and the long axes of some of the larger quartz grains impart a planar tendency that is not definite enough to be called gneissic. Sporadic large grains of quartz and feldspar are visible.

In thin section the rock shows the typical granoblastic fabric of metaquartzite—a mosaic of quartz (with mild undulatory extinction), microcline, and plagioclase, generally albite. The average grain size of the mosaic is 0.2 to 0.5 mm, with some grains reaching 3 to 5 mm. The mica plates show a preferred orientation, but no mineral segregation into bands, that is, development of a gneissic fabric, has taken place. Table 1 gives the modes of some representative quartzites. On the average the quartzites are composed of 80 to 95 percent quartz and feldspar. Microcline, characteristically twinned, may make up as much as 40 percent of the entire mineral composition of the rock (range 5 to 40 percent, average 20 to 30 percent). Plagioclase, which may or may not show polysynthetic twinning, has been observed to make up as much as 15 percent of the rock (range 2 to 15 percent, average 5 to 10 percent). The anorthite content of the plagioclase ranges from 5 to 20 percent, averaging about 10 percent. Most of the feldspar occurs as an integral part of the mosaic, but in a minor category some small rounded inclusions of feldspar are present

within the quartz. This may indicate a tendency toward a "sieve" fabric. Recrystallization of a feldspathic quartz sandstone provides a satisfactory explanation of the origin of these rocks.

Mica, either muscovite or biotite, or both, is well oriented. The biotite is a green-brown variety, $\gamma = 1.600$–1.650, and shows a variable degree of alteration to bleached biotite, or bauerite.

Zircon, magnetite or ilmenite, leucoxene, and apatite are present as accessory minerals.

Muscovite Schist.—Feldspathic muscovite schists, commonly biotitic, make up to 50 to 60 percent of the entire Precambrian section. They form a glittering white outcrop of rather soft rock that crumbles into a micaceous sand under the hammer. These rocks possess characteristic schistosity and foliation.

Thin section shows parallel plates of mica in a granoblastic aggregate of quartz and feldspar. The quartz shows a mild undulatory extinction. Excepting the higher content of mica, this rock is in every way similar to the quartzites just discussed. The muscovite content is rarely over 30 percent and averages 15 to 25 percent. Microcline, plagioclase (albite and albite-oligoclase), magnetite or ilmenite, and zircon are also present. The average grain size of the mosaic is 0.2 to 0.5 mm with the mica laths averaging 1 by 0.2 mm. Table 1, IV, gives the mode of a representative muscovite schist.

Chemical analyses of quartzo-feldspathic rocks are given in Table 2.

Petrography of the Amphibolite-Biotite Schist Sequence.

Intercalated with the quartzites and muscovite schists are small lenses and beds of biotite schist, amphibolite, and epidote rock or epidotite.

Biotite Schists.—The biotite-bearing rocks of the Mica Mine area have a varied mineralogy. They seem to represent a transition between the potash-rich muscovite-microcline-quartz rocks on the one hand and the potash-deficient hornblende-plagioclase rocks on the other. Not uncommonly an amphibolite bed of some 5 to 10 feet in thickness is separated from the muscovite schists by several feet of biotite schist or biotite-albite schist. A rock containing biotite, amphibole, and plagioclase frequently occurs as a transition unit between biotite schists and amphibolites composed solely of hornblende and plagioclase. Thus the biotite rocks fall into two classes: (a) normal biotite-quartz schists and (b) biotite-amphibole-plagioclase rocks.

The biotite-quartz schists in beds up to 15 feet thick form a glittering black outcrop in the Mica Mine area. Biotite plates several millimeters in diameter, red-stained quartz, and a white feldspar are visible in the hand specimen. Commonly a rucking is present, with the amplitude of the tiny fold on the order of several millimeters.

Thin section shows parallel plates of biotite in a mosaic of quartz and albite. There is a marked variation in size among the grains of the mosaic (0.5 mm is a fair average). The rock is composed of about 40 to 60 percent quartz, 10 to 20 percent albite (microcline may be present), and 30 to 40 percent biotite. The biotite of this rock is an olive-brown variety ($\gamma = 1.662 \pm 0.002$). One section shows 3 percent garnet restricted to a narrow zone parallel to the foliation. Apatite, sphene, leucoxene, magnetite or ilmenite, rutile, and carbonate occur in minor quantities.

The biotite of the biotite-plagioclase (with or without amphibole) schists reflects a potassic phase of the general amphibolite assemblage. Hornblende, anthophyllite, epidote, and sphene may accompany biotite in this phase. The hand specimen is a more massive rock than above. The biotite occurs in small flakes (1 mm or less) and makes up less of the total mineral assemblage.

Thin section shows a mosaic of albite-oligoclase averaging 0.5 mm in grain size and making up 50 to 75 percent of the rock. The plagioclase is more or less altered to sericite. Biotite, an olive-brown to red-brown variety ($\gamma = 1.660$ to 1.700), makes up 10 to 30 percent of the rock and again shows a parallel orientation. The biotite laths average 0.2 by 1 mm. Some specimens contain amphibole—blue-green hornblende or anthophyllite. The hornblende occurs in poikilitic crystals or subhedral prisms aligned with the biotite. The anthophyllite occurs in bladed or fan-shaped porphyroblasts up to 10 or 20 cm in length. Minor quartz, ilmenite or magnetite, sphene, leucoxene, apatite, and carbonate may be present. Platy ilmenite (associated with leucoxene) may occur in biotite cleavages.

Amphibolites.—Four main types of amphibolite can be distinguished: (a) amphibolite, (b) almandine amphibolite, (c) anthophyllite amphibolite, and (d) epidote amphibolite (grading into epidotite).

The normal amphibolite (a) is a massive green-black rock in which, on close inspection, minute prisms of hornblende are visible. These prisms may show a fair lineation or they may occur in a mat of non-lineated prisms parallel to the general foliation of the area and imparting a rude schistosity. The average length of the hornblende prisms is 1 to 3 mm. Local coarsenings are common. Hornblende may make up as much as 70 percent of the rock. Plagioclase is the only other major mineral.

Under the microscope this rock shows poikilitic hornblende prisms in a mosaic of untwinned plagioclase. The hornblende is a blue-green variety with $Z \wedge C = 16$ to 18 degrees, $\beta = 1.665$ to 1.672, and negative optic sign. These determinations, unless otherwise stated, hold true for blue-green hornblende of all amphibolite types. The hornblende averages 30 to 50 percent of the rock but may range as high as 70 percent. The plagioclase (oligoclase-andesine) has the same percentage range in amount as the hornblende (average, 30 to 50; maximum, 70). It invariably shows some degree of alteration to sericite. An inverse zoning, characteristic of the plagioclase of many metamorphic rocks, can be seen in most sections. Quartz is generally present in amounts less than 10 percent. Quartz-rich layers were observed in some thin sections, and in these layers the quartz content may be as high as 25 or 30 percent. The quartz is easily distinguished from the altered plagioclase. Magnetite or ilmenite (4 to 5 percent) and apatite (1 to 2 percent) are present. The average grain size of the mosaic is 0.2 to 0.4 mm. The hornblende prisms average 1 to 2 mm in length.

Almandine amphibolite (b) was observed in one outcrop (see 19.3-F.O, Fig. 2). Here the normal green-black amphibolite contains porphyroblasts of garnet averaging between 5 mm and 1 cm in diameter and making up 10 to 15 percent of the rock. They weather out in perfect dodecahedrons. The garnet is deep red and has a specific gravity of 4.14. The mass of the rock consists of 40 to 50 percent lineated prisms of blue-green hornblende in a mosaic of plagioclase (oligoclase-andesine). There is no distortion or bending of the hornblende prisms where they abut the garnet. Inclusions of magnetite in the garnet show a lineation at an angle to the lineation of the rock as a whole and may be evidence of rotation. The plagioclase makes up about 30 percent of the slide and is partly altered to sericite. Magnetite or ilmenite makes up 5 to 8 percent of the rock. Apatite, in rounded grains, may make up as much as 3 percent.

Anthophyllite amphibolite (c) is in contact with the almandine amphibolite and is different from the biotite-anthophyllite rock previously described. The hand specimen is a massive green-black rock with bladed porphyroblasts of anthophyllite, on the

order of 1 by 15 mm, showing fair lineation. Thin section shows a mosaic (0.1 to 0.2 mm) of andesine containing oriented prisms of blue-green hornblende. The plagioclase and hornblende each make up about 40 percent of the slide. Large poikilitic porphyroblasts of anthophyllite constitute the remaining 20 percent of the rock. The anthophyllite blades, averaging about 1 cm in length, show no orientation and cut across the lineation of the hornblende.

In contact with the rock just described is another anthophyllite rock. It is composed of 50 percent andesine and 40 percent anthophyllite, with complete absence of hornblende.

Epidote-bearing amphibolites (d) are distributed through a more or less linear zone in the northern schist outcrop. With the appearance of a substantial epidote content the normal green-black amphibolite takes on a waxy green cast. Yellow-green streaks show up in the darker hornblende-bearing rocks, and these streaks may develop into layers of an aphanitic waxy yellow-green rock containing scattered magnetite crystals. These layers are discontinuous and about 1 to 2 inches thick. This rock conforms to the description of an epidotite (7).

The epidote amphibolite consists of a mosaic of quartz and oligoclase containing blue-green poikilitic hornblende prisms, grains, and granular masses of epidote and grains of sphene. There is some tendency for the hornblende and quartz to be concentrated in layers.

The rock is composed of 10 to 30 percent well-lineated prisms of blue-green hornblende, 10 to 50 percent plagioclase, and a variable amount of epidote and quartz. The oligoclase shows alteration to sericite. Quartz is in amounts less than 10 percent, although in one section it reaches as high as 30 percent. Epidote, distinctly yellow in thin section, ranges from 10 to 20 percent up to 60 to 70 percent, at which point the rock may be classed as an epidotite. The epidote is clearly a metamorphic mineral and occurs as small discrete grains (0.5 to 0.1 mm) and groups of grains. Sphene makes up 1 to 3 percent of the rock. Ilmenite is a common accessory and may make up as much as 5 percent of the total composition.

Aphanitic waxy yellow-green rocks occurring in streaks and layers within the epidote amphibolites are here called *epidotites*.

The epidotites of the Mica Mine area contain 80 to 90 percent granular epidote in grains 0.04 to 0.06 mm in diameter and 8 to 10 percent albite or albite-oligoclase, usually altered. Sphene makes up 2 to 4 percent of the rock. A dark-green hornblende may be present in amounts up to 5 percent. The fabric is crystalloblastic.

Quartz Veins.

Veins of white quartz containing variable amounts of biotite and hematite occur within the Mica Mine area. They are mostly restricted to a north-south zone (Fig. 2), indicating an old locus of fissuring. The location of minor quartz veins is in places controlled by the hanging or footwall of pegmatites, and the veins are, therefore, later than the pegmatites.

The veins are the product of high-temperature hydrothermal solutions carrying iron and silica. The reaction of these iron-bearing solutions with the potash and alumina of the wall rocks formed biotite, commonly in sheaf-like masses. Discontinuous and distorted masses of quartz and biotite conforming to the structure of the metamorphic rocks may be interpreted as the product of pre-metamorphic or syn-metamorphic hydrothermal solutions.

Permian Rocks.

Permian rocks rest on the Precambrian rocks of the Van Horn Mountains with marked angular unconformity. On the basis of lithologic character and

megafauna the Permian section of the Mica Mine area is assigned to the Wolfcamp. Two lithologic units can be distinguished: (1) a conglomeratic sandstone and (2) a compact aphanitic gray cherty limestone.

The sandstone is extremely varied in thickness and the thickness is controlled by irregularities in the old Precambrian surface. On old Precambrian hills the limestone rests directly on Precambrian rocks while in low places on the old surface as much as 250 feet of sandstone is present. The rock is a fine-grained red and brown micaceous feldspathic sandstone containing sporadic pebbles of quartz, feldspar, and pegmatite. In the southern part of the Mica Mine area, 20 to 30 feet of boulder conglomerate is present at the base of this clastic unit. Boulders of schist, quartzite, and pegmatite reach diameters of 3 to 4 feet. The sandstone grades into the overlying limestone through a 20 to 30-foot zone of interbedded silty limestone and sandstone.

Comformably overlying the clastic unit is a compact aphanitic gray cherty limestone. This rock occurs in beds 6 inches to 6 feet thick and forms bold cliffs around the exposed Precambrian rocks. Diagnostic features are the abundance of brown chert in stringers, nodules, and irregular masses; crystalline calcite in veinlets and lining cavities; nodules of manganese dioxide in cavities; silicified echinoid spines and plates; and strong fetid smell on breaking.

Cretaceous Rocks.

Unconformably overlying the Permian limestone is a brown Cretaceous sandstone that marks the top of the Trinity. In the Mica Mine area this rock is generally in contact with the Permian only along faults. The rock is a medium to coarse-grained sandstone; well indurated (locally it is an orthoquartzite) and well sorted. It is composed mostly of quartz with a small amount of altered feldspar (less than 5 percent) and less than 1 percent magnetite. The grains are sub-round. Bands of chert and quartz pebbles and cross-bedding are common. Thin beds of silty limestone and limestone and chert pebble conglomerates occur within the sandstone. Masses of oyster shells occur locally in the limestone beds. This sandstone is overlain by the basal Fredericksburg Finlay limestone to the east of the Mica Mine area.

Igneous Rocks.

Trachyte and analcime-bearing diabase dikes occur in the Mica Mine area. From the field evidence these intrusions cannot be assigned to a definite age. The trachytes cut Permian rocks. On the basis of similarity to rocks described by Lonsdale (17) and Baker (4) the writer believes these dikes to be Tertiary (?).

PEGMATITES.

More than eighty pegmatite bodies at least 1 foot thick were mapped in the Mica Mine area. They are relatively resistant and form prominent topographic features. The pegmatites consist of an aggregate of microcline perthite, quartz, plagioclase (albite and oligoclase), muscovite, and tourmaline (schorlite). Biotite and spessartite garnet occur in a very few pegmatites. Internal zoning can be distinguished in about 30 percent of the pegmatites.

Pegmatite bodies occur in all parts of the metasedimentary series, but they are more abundant in the schistose rocks than in the massive quartzites. They range in size from stringers less than 1 inch thick to lens-like bodies as much as 150 feet thick. The shape of the pegmatites varies widely. They may be more or less tabular bodies, irregular bodies with tabular branches, irregular masses, elongate lenses, small augen, or thin stringers, either as separate bodies or as groups in *lit-par-lit* zones.

Relation to Host Rock.

Most of the pegmatites are tabular or lens-like bodies that conform to the foliation of the host rock. It is not uncommon for a body, that is for the most part conformable, locally to distort the foliation of the country rock. Rolls and minor undulations of the contact are common. Some pegmatites are concordant in part but have discordant forks or branches. A few small pegmatites are in fractures that cross-cut massive quartzite.

Relation to the Quartzite and Muscovite Schist.—The contact between the pegmatite bodies and the quartzites or muscovite schists is either a planar surface or a *lit-par-lit* zone 1 to 5 feet wide, depending on the presence and attitude of schistosity in the invaded rock. There is no alteration of the wall rock at the contact. A thin section across ¼-inch feldspar-quartz-muscovite pegmatite in a feldspathic muscovite schist shows that the pegmatite is a panallotriomorphic aggregate of quartz and feldspar with a high albite content, and the muscovite schist is a typical unaltered lepidoblastic quartz-microcline-muscovite rock. Along the contact the schist shows the beginnings of a sutured mosaic. A concentration of strained and bent muscovite plates along the plane of contact between pegmatite and schist indicates that the pegmatite was emplaced under stress. The presence of a sub-round zircon in the pegmatite (similar to those found in the schist) and a faint trace of mosaic structure in the pegmatite quartz may indicate that some of the pegmatite material was derived from the host rock by a process of digestion and recrystallization.

Relation to the Amphibolite and Biotite Schist.—Pegmatites in contact with amphibolite have a narrow zone, less than 6 inches wide, of biotite amphibolite at the contact. The biotite occurs in discrete laths in contact with hornblende and does not rim or interfinger with hornblende. Pegmatites in contact with biotite schist apparently have not altered their wall rocks.

The pegmatites in contact with biotite schist or amphibolite contain minerals that reflect the composition of the wall rock. Pegmatites in contact with amphibolite contain spessartite garnet, biotite, and plagioclase with an anorthite content that is approximately 10 percent higher than that of plagioclase in pegmatites in contact with muscovite schists and quartzites. The pegmatites in contact with biotite schist contain biotite and spessartite, but the plagioclase does not have a high anorthite content. In both types of pegmatites the spessartite and biotite have a spotty and uneven distribution. The presence of spessartite and biotite only in those pegmatites in contact with biotite schist and amphibolite is definite evidence of contamination.

Schist Inclusions.—Nearly all of the Mica Mine area pegmatites contain inclusions of country rock. These inclusions form partitions parallel to the

contact of the pegmatite (and the foliation of the host) or irregular blocks. In the more schistose areas partitions are especially common. They exhibit all stages of digestion [4] and recrystallization and grade into rock that is essentially pegmatite. Only the finer grain size and the even texture of the digested rock enable the observer to distinguish it from pegmatite. On occasion a partition of schist thins and passes into a mica-rich streak. Small mica books commonly grow at right angles to the contact of schist and pegmatite.

A number of thin sections of inclusions in various stages of "pegmatization" were studied. The following points were noted:

(1) The straight-line grain boundaries of the former mosaic of the muscovite schist inclusions are changed to the very irregular contacts of a sutured mosaic (Figs. 3–5).
(2) Quartz is coarser grained and shows marked undulose extinction. Traces of former grain outlines may indicate a welding of the smaller quartz grains of the normal schist (Fig. 5).
(3) Bent muscovite crystals are common (Fig. 4).
(4) Plagioclase surrounds islands of quartz and microcline (Fig. 7), and quartz embays plagioclase and microcline (Figs. 6, 8).
(5) Simultaneous growth of minerals may result in a "sieve" fabric (Fig. 9).
(6) Veinlets of quartz, quartz and muscovite or sericite, or quartz and feldspar cut earlier minerals (Figs. 10, 11).

The minerals of the schist inclusions show strain and therefore have not completely recrystallized.

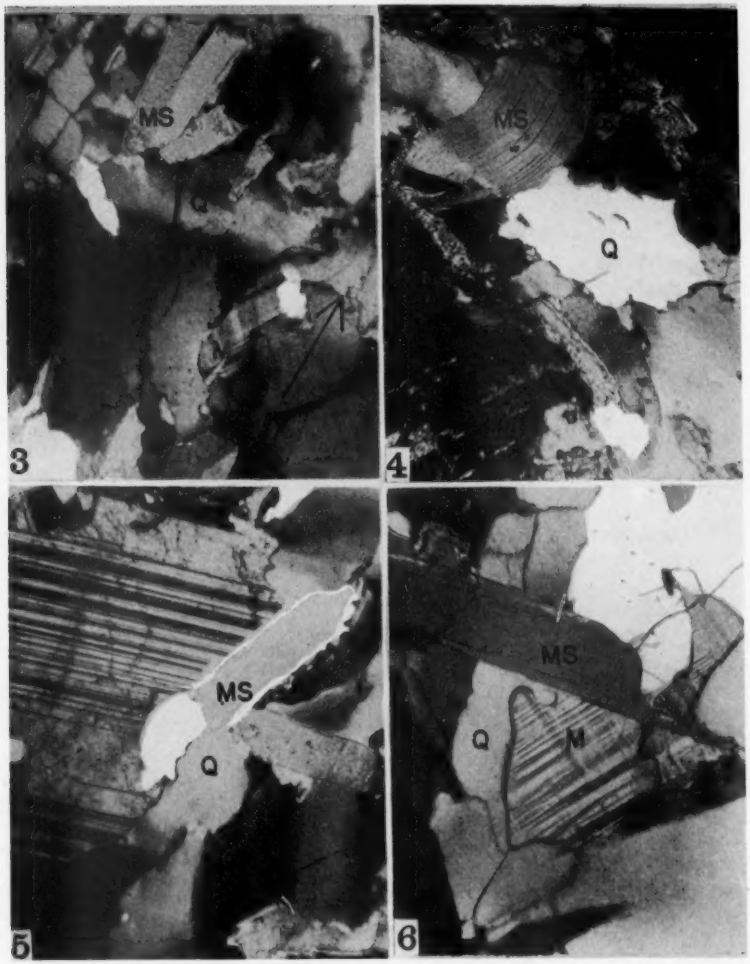
Internal Structure.[5]

More than one-third of the pegmatites mapped in the Mica Mine area are bizonal. A wall zone and a core, commonly discontinuous, form the two units of the zoned pegmatite.

Wall Zone.—The wall zone of all the pegmatites in the area consists of blocky subhedral crystals of microcline perthite (size range 1 to 8 inches long, average 3 to 4 inches long) in a fine-grained matrix with grains which range from $\frac{1}{16}$ to 1 inch long and average $\frac{1}{4}$ inch long. The blocky perthite averages 30 to 40 percent of the wall zone and ranges from 10 to 80 percent. The fine-grained matrix is composed of subhedral microcline perthite, plagioclase, quartz, and muscovite. In most pegmatites the larger part of the feldspar in the wall zone is plagioclase, although the relative proportions of the two feldspars, plagioclase and microcline perthite, vary widely. The wall zone averages about 60 percent microcline perthite and plagioclase. Muscovite, in small books, ranges from 2 to 10 percent and averages 5 percent of the zone. Quartz makes up the remainder. Chemical analysis of a representative sample of the wall zone is given in Table 2, IV. Some pegmatites contain intergrowths of quartz and muscovite up to 8 inches in diameter (called mica aggregate or "bull" mica

[4] *Digestion* is defined as replacement in an essentially closed system.

[5] The use of the term *zone* in this paper conforms to that of Cameron et al. (5). A zone is a structural or lithologic unit that in general reflects the shape of the pegmatite body. It is distinguished from fracture fillings and replacement bodies and is considered to be a primary rather than a secondary feature of the pegmatite.



FIGS. 3–6. M, microcline; MS, muscovite; Q, quartz. × 70.

FIG. 3. Muscovite schist inclusion. Note sutured mosaic (arrow) and straining in quartz.

FIG. 4. Muscovite schist inclusion. Note sutured mosaic, bent muscovite, and strained quartz.

FIG. 5. Muscovite schist inclusion with pegmatite seams parallel to the foliation. Note former grain boundaries of quartz (arrow), and sericite rimming muscovite.

FIG. 6. Muscovite schist inclusion almost completely pegmatized. Note embayed and corroded microcline in the quartz.

in the trade). These intergrowths seem to be distributed for the most part within the inner part of the wall zone.

Core.—The core is a relatively narrow zone, commonly discontinuous, of coarse microcline perthite and massive white quartz. It is rarely over 2 or 3 feet thick. Microcline perthite crystals (range 4 inches to 3 feet long, average 6 to 10 inches long) make up 60 to 70 percent of the core. Included quartz, commonly in a rude graphic intergrowth, is found in some perthite crystals. In a few pegmatites muscovite books 3 to 4 inches in diameter may occur in or on the periphery of the core. Nearly all of these books are "wedged" and show "rulings" and "A" structure.

Sequence of Zones.—From the data gathered in various pegmatite districts, Cameron et al. (5) have formulated an ideal sequence of zones which are said to occur invariably in the same order with relation to each other. Some zones in this sequence may be absent and/or telescoped in different districts. Zones three and four (from the wall inward) in the ideal sequence are: (3) quartz-perthite-plagioclase with or without muscovite, with or without biotite and (4) perthite-quartz. In the Mica Mine area these zones form the wall zone and core respectively. The preceding zones (plagioclase-quartz-muscovite and plagioclase-quartz) and the succeeding lithium-bearing zones of the ideal sequence are not present in the Mica Mine area.

Fracture Fillings.—Fracture fillings of quartz and perthite; quartz, perthite, and tourmaline; quartz and tourmaline; and quartz cut the wall zone.

Replacement Unit.—In the Mica Mine No. 1 (Fig. 14) a plagioclase-quartz replacement unit was mapped.

Comparison of Zoned and Unzoned Pegmatites.—In the Mica Mine area zoned and non-zoned pegmatites of identical mineralogy are closely associated. In some places only the wall zone is exposed; in others the full thickness of the pegmatites is exposed. Rectilinear dike-like bodies with sharp contacts and no schist partitions show the best zoning. Pegmatite bodies containing many schist partitions show no discernible zoning, although local areas of coarser quartz and perthite occur throughout the pegmatite. In dike-like bodies these "shoots" of coarse quartz and perthite are parallel to the walls of the body. An idealized section made from a sketch (Fig. 13) shows the effect of a schist partition on the development of a core. The obvious conclusion is that the schist partitions interfered with the crystallization of the pegmatite body as a unit, separating it into a number of poorly connected cells.

Mineralogy and Mineral Relations.

The pegmatites of the Mica Mine area are simple feldspar-quartz-mica pegmatites containing microcline perthite, plagioclase, quartz, muscovite, tourmaline, biotite, spessartite, and magnetite. No rare-earth minerals, lithium minerals, or phosphates were found.

Microcline Perthite.—Blocky crystals of microcline perthite make up, on the average, 30 to 40 percent of Mica Mine area pegmatites. The microcline perthite is usually pink but may be white, flesh-colored, or salmon. The pink color may reflect the iron content of the mineral. Salmon-colored microcline

perthite occurs in those pegmatites within the amphibolite-biotite schist sequence. The microcline perthite in the wall zone and core is in subhedral crystals that are resistant to weathering and form rough blocky outcrops. These large perthite crystals are distributed in the pegmatite like phenocrysts in a giant porphyry.

The microcline perthite varies from a clean almost glassy feldspar to an opaque feldspar containing inclusions of quartz and muscovite. The latter type is the most common. A rude graphic intergrowth of quartz and microcline is common; good graphic granite is rare and is restricted to the inner part of the wall zone.

Perthitic structure can be seen in the hand specimen as a network of fine anastomosing bands approximately 1 mm wide. A photomicrograph of this perthitic structure is shown in Fig. 12. This perthite is similar to what Andersen (1) described as "vein perthite." The regular parallel plagioclase lamellae show, on a small scale, an irregular contact with the microcline. This may indicate replacement of microcline by plagioclase along the contact. The anorthite content of the plagioclase from six microcline perthites (from both wall zone and core) was determined and compared with the wall-zone plagioclase from the same pegmatite. In each pegmatite the anorthite content of the plagioclase from the microcline perthite is 1 or 2 percent less than the anorthite content of wall-zone plagioclase. There is no plagioclase in the core other than that perthitically intergrown. These points seem to favor the hypothesis of origin of perthite by exsolution rather than by replacement.

Plagioclase.—Plagioclase occurs only in the fine-grained pegmatite of the wall zone where it is associated with potassium feldspar. The color ranges from white to flesh, and the latter is almost impossible to distinguish from flesh-colored microcline perthite in the fresh sample. On weathered surfaces the plagioclase, being more susceptible to alteration than microcline perthite, is more easily recognized. Plagioclase is generally more intimately intergrown with quartz than is the microcline perthite (which tends to be subhedral), and this aids in identification. An accurate determination of the percentage of plagioclase in the fine-grained pegmatite is almost impossible. The writer estimates 30 to 50 percent plagioclase in the fine-grained pegmatite of the wall zone and 20 to 40 percent in the pegmatite as a whole. Plagioclase is not found in the core.

The anorthite content of the plagioclase was determined by the immersion technique for each pegmatite shown on Figure 2. The total range for the district was An_1 to An_{24}. The values may be grouped as follows:

(1) Abnormally high values of An_{20} and An_{24} were found in the two pegmatites in contact with amphibolite. Plagioclase from these pegmatites was varied in composition but showed consistently high anorthite content. These values in the oligoclase range appear to be the result of contamination by digestion of amphibolite country rock by the pegmatite. The variation of anorthite content of the plagioclase within the pegmatite suggests that the more anorthitic varieties occur in areas of greater contamination and that equilibrium between the contaminated pegmatite and the normal pegmatite material was not reached.

(2) The plagioclase of pegmatites near the mill (Fig. 2), including the Mica Mine No. 1, shows low anorthite values ranging from An_1 to An_7.
(3) The plagioclase in the pegmatites south of the canyon running east of the mill shows a decrease in anorthite content from An_9 in the north to An_5 at the southern limit of the area.
(4) North of the canyon east of the mill the anorthite content of plagioclase increases from An_9 to An_{14} at the northern limit of the area.

Except for the small area just east of the mill there is a general increase in the anorthite content of the plagioclase from relatively pure albite in the south to oligoclase in the north. Unfortunately there is not enough area exposed to reveal any systematic pattern.

Thin sections of the fine-grained pegmatite show plagioclase embaying quartz and microcline and being embayed by quartz and veined by quartz or quartz and muscovite.

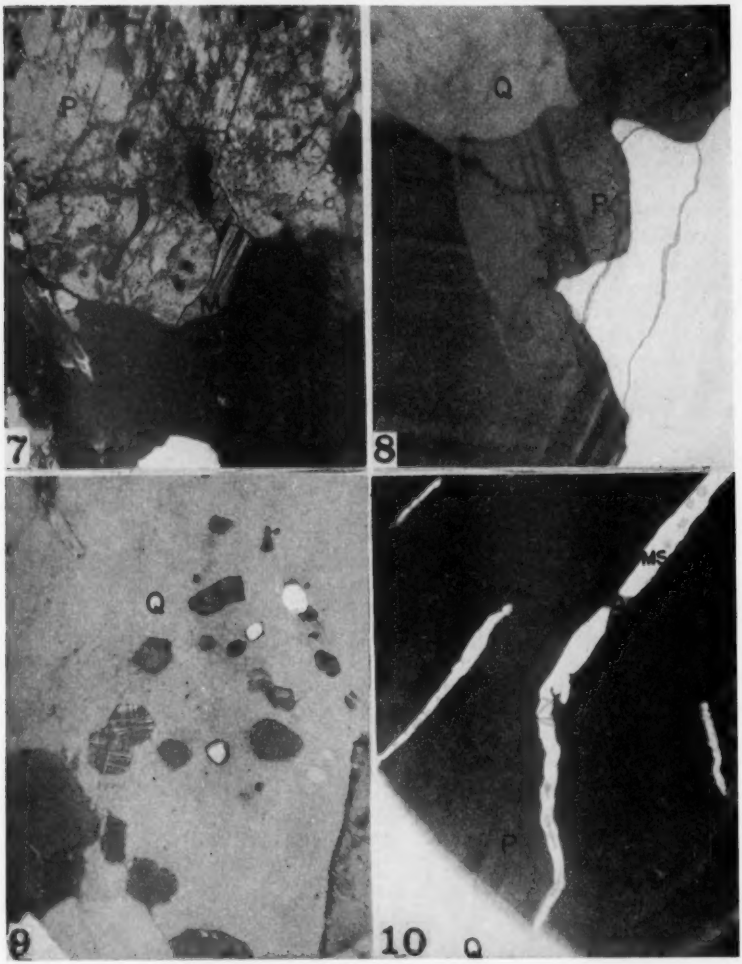
Quartz.—Quartz occurs in the fine-grained pegmatite of the wall zone, in the core, and in fracture fillings. In the wall zone the quartz is intergrown with feldspar and muscovite, making up about 30 percent of the zone. In the core massive white quartz occurs with the perthite and makes up about 30 percent of the zone. In non-zoned pegmatites, masses of white quartz commonly occur throughout the body. Black tourmaline is commonly intergrown with this massive quartz. In facture fillings, quartz may be accompanied by perthite and tourmaline or by tourmaline alone.

Microscopic study of thin sections shows that the quartz within the pegmatite is badly strained and that small quartz veinlets cut previously crystallized pegmatite minerals (Figs. 10, 11). Quartz embays plagioclase and microcline and is frequently replaced by plagioclase.

Muscovite.—The muscovite of the Mica Mine area is a silver-gray to gray-green variety. It occurs in small plates and books within the fine-grained pegmatite, of a size with the fine-grained pegmatite, and as larger books within the core, along the margin of the core, and in local coarse-grained segregations. Muscovite also occurs in intergrowths with quartz (mica aggregate) and in thin sheets in cracks and along crystal boundaries in the wall zone. One pegmatite, the Mica Mine No. 1 (Fig. 14), contains large books of muscovite in a zone of partly kaolinized feldspar cut by numerous quartz-tourmaline stringers.

The muscovite can be divided, on the basis of field observations, into primary muscovite (contemporaneous with the associated minerals) and secondary muscovite (later than the associated minerals). Primary muscovite occurs in the wall zone and core.

The muscovite in the fine-grained pegmatite is in more or less equilateral books that make up on the average of 2 to 4 percent of the fine-grained pegmatite. This muscovite is evenly distributed and is an integral part of the mineral aggregate. An occasional mica book may be somewhat larger than the accompanying minerals. In the Mica Mine No. 1 (Fig. 14) muscovite books up to 8 inches in diameter are found. Although stained and spotted, these books split well. In this zone of abnormally large (for the district) mica books, the surrounding feldspar is partly kaolinized, and the pegmatite is cut



FIGS. 7–10. M, microcline; MS, muscovite; P, plagioclase; Q, quartz. × 75.

FIG. 7. Muscovite schist inclusion almost completely pegmatized. Note remnants of quartz (dark) and embayed microcline remnant (outlined) in the plagioclase.

FIG. 8. Muscovite schist inclusion with pegmatite seams parallel to the foliation. Note quartz embaying plagioclase.

FIG. 9. Muscovite schist inclusion with "sieve" fabric.

FIG. 10. Fine-grained pegmatite. Note quartz-muscovite veinlet extending from quartz grain across plagioclase grain.

by numerous quartz-tourmaline stringers. These large books may be the result of prolonged growth or regrowth of mica under the influence of late solutions.

Roughly elliptical or circular masses of intergrown quartz and muscovite with minor feldspar, known as "mica aggregate" and "bull mica" in the trade, are present in a great many pegmatites. The intergrowths are 2 to 5 inches in diameter and are made up of individual grains ¼ to ½ inch in size. They seem to be restricted to the inner part of the wall zone. They are composed of approximately 60 percent muscovite and 40 percent quartz with the muscovite books oriented in a fan. The lack of muscovite in the surrounding pegmatite indicates that these segregations are primary. The mechanics by which this segregation of quartz and muscovite was affected are not readily explainable. The regularity of size and distribution of the intergrowths in the areas where they occur precludes the possibility that they are reconstituted schist fragments.

Books of muscovite 1 to 3 inches in diameter occur within the core, along the core margin, and in local coarse segregations. These larger books are everywhere associated with coarse perthite and quartz phases. Nearly all these books are "wedged" and "ruled." Just east of the mill (Fig. 2), however, a number of pegmatites contain muscovite books that split very well. This mica is heavily stained and spotted and may be classed as "electrical mica."

Secondary muscovite occurs in cracks and along crystal boundaries as thin sheets and films in the wall zones of most pegmatites in the Mica Mine area. Commonly these thin sheets assume a "bird-foot" arrangement, occupying short radial cooling (?) cracks. Muscovite sheets and films also occur along the boundaries of perthite crystals. This muscovite is later than the accompanying minerals and is the result of penetration of the crystallized pegmatite, along planes of weakness, by the unconsolidated pegmatite fluids. Sericite rims around muscovite, concentrations of sericite along grain boundaries, and veinlets of sericite are seen in thin sections and show there has been transfer of sericite material through the crystallized pegmatite.

Tourmaline.—Black tourmaline, variety schorlite (E, pale pink-brown; O, deep blue-black), is present in quantities of 2 percent or less in nearly all the pegmatites. Tourmaline is intergrown with quartz in the cores, in local coarse segregations, and in fracture fillings. It also occurs as needles coating joints, perthite boundaries, and in quartz stringers. Quartz-tourmaline stringers, in part containing plagioclase, cut the wall zone and the contact of schist and pegmatite. At one place a quartzite near the contact of the pegmatite has been tourmalinized to form a quartz-tourmaline gneiss. There is no tourmaline associated with the quartz veins of the Mica Mine area.

Although tourmaline was very late in the sequence of crystallization, some quartz was deposited still later in minute veinlets that cut the tourmaline crystals.

Biotite.—Biotite occurs only in those pegmatites in contact with biotite schist or amphibolite. The biotite is in books intergrown with the quartz and feldspar and in thin sheets along crystal boundaries. In one pegmatite where

the footwall is in contact with amphibolite, biotite is restricted to the footwall wall zone of the pegmatite. It is certain, then, that the elements necessary to the formation of biotite were derived from the host rock. As a corollary, the biotite in individual pegmatites is variable in composition, ranging from a green-brown to a red-brown variety according to the composition of the contaminating rock. A range in γ from 1.650 to 1.680 was found.

Spessartite.—Spessartite is present only in pegmatites in contact with biotite schist or amphibolite and occurs as idiomorphic cinnamon-brown garnets in separated bunches. The specific gravity of the garnet was measured as 3.39. Winchell gives the specific gravity of spessartite as 3.80 to 4.25. The low specific gravity of the garnet of the Mica Mine pegmatites is caused by small quartz inclusions within the crystals. The garnet has a sporadic and uneven distribution and frequently occurs as inclusions within the large blocky perthite crystals. This suggests an uneven distribution of the contaminated material.

Magnetite.—Occasional small crystals of magnetite occur in those pegmatites that are in contact with the amphibolites and biotite schist.

ORIGIN OF THE PEGMATITES.

During the past decade a detailed and comprehensive study of pegmatites has been made by the U. S. Geological Survey. Part of the results of these pegmatite studies have been published (5). This work and other recent work on pegmatites have presented a great deal of information on the nature of pegmatite bodies but have not solved the problems of (a) the relative importance of primary versus secondary processes in the formation of complex pegmatites, (b) the nature of the pegmatite fluid, and (c) the mode of emplacement of pegmatites.

There are a number of definitions of the term *pegmatite,* many of which are undesirable because of connotations of mode of origin. The writer favors the definition given by Andersen (2, p. 3): "Pegmatites are mineral associations crystallized in situ, decidedly more coarse grained than similar mineral assemblages in the form of ordinary rocks and differing from those in having a more irregular fabric of the mineral aggregate." Although somewhat unwieldy, the definition has the merit of being free from all references to genetic processes.

Many geologists use the term *pegmatite* in conjunction with the term *dike,* as *pegmatite dike.* The difference between pegmatite bodies and normal igneous dikes is certainly great. Andersen (2, p. 5) has remarked that: "It is true that many of these bodies [referring to pegmatites] apparently have some of the essential characteristics of dikes, such as parallel walls, but a large number of them have forms of such indefinable irregularity that by no stretch of the definition of the term is it possible to classify them as dikes. When other features are considered no pegmatite body to my knowledge answers the description of a typical igneous dike." A normal igneous dike may be defined as a solidified mass of magma injected during a single pulse and occupying a

rectilinear fissure.[6] A straight course and a closed system are embodied in this definition. A pegmatite is certainly vastly different from a rhyolite dike, although the chemical composition of the two may be similar.

An excellent summation of the history of the term *pegmatite* and earlier theories of origin of pegmatites is given by Johannsen (14).

Theories of Origin.

Any comprehensive theory of origin of pegmatites must account for certain features characteristic of pegmatites as a whole as well as features peculiar to the district studied. A satisfactory theory must explain the wide variations in pegmatite geology and mineralogy. The following are, in the writer's opinion, the major features of pegmatite occurrence that a theory of origin must explain:

(1) Pegmatites have a common areal association with bodies of rock generally considered igneous in origin. In some places there is an obvious comagmatic relation between pegmatite and intrusive, for example, syenite-pegmatite and syenite intrusive, but this relation does not always hold; for example, the differentiation of a gabbroic magma may produce syenite-pegmatite.
(2) In some districts pegmatites contain rare and unusual minerals. Some of these minerals are virtually restricted to pegmatites, some are common in igneous rocks, and some are found in hydrothermal veins. In general, however, only a very small percentage of pegmatites contain rare minerals; most are simple quartz-feldspar bodies.
(3) Pegmatites have distinctive textures, the most prominent of which is coarse and irregular grain size.
(4) Some pegmatites show a regular and systematic internal structure which is reflected in units of varied composition and texture.
(5) Pegmatites commonly assume extremely diverse and irregular forms and penetrate the host in a very intimate fashion.
(6) The composition of some pegmatites is influenced by the composition of the wall rock. Other pegmatites cut across wall rocks of widely differing characters and show no evidence of having been affected by the wall rocks in any way.
(7) Wall-rock alteration is associated with some pegmatites. The alteration takes the form of tourmalinization, biotization, feldspathization, silicification, or introduction of such pegmatite minerals as muscovite and beryl. This alteration is not comparable to the sericitization and kaolinization accompanying normal hydrothermal veins.
(8) Pegmatites commonly distort the foliation of the host rock or impress a secondary foliation on the host.
(9) Pegmatites are commonly associated with aplites.

There are a number of theories of origin of pegmatites which place different interpretations on the physical evidence or which emphasize some features to the neglect of others.

The Granitization Theory.—There are two different ideas on pegmatite formation within the granitization school. One concept holds that pegmatites represent preferred directions of granitization (or pegmatization) and that the volumes now occupied by pegmatite were formerly occupied by country rock

[6] Knopf, Adolph, Lecture, 1949.

(10, 15, 19). This is essentially a theory of selective metasomatism. The second concept holds that a low-temperature liquid rich in expelled elements forms in advance of a theater of granitization and is injected into fissures under hydrostatic pressure (3).

The hypothesis of pegmatization by metasomatism in preferred directions fails to explain a number of the major features of pegmatite occurrence. They are summed up as follows: (1) The presence of textural and mineralogical zones reflecting the shape of the pegmatite body and often containing systematic concentrations of rare elements. Core zones are frequently isolated pods; (2) Evidence of injection (dilation, rolls, distortion of foliation); (3) Wall-rock alteration; (4) Fracture fillings extending from the core and cutting wall zone and host rock; and (5) Pegmatite textures. The process of granitization is one in which a mass of crustal rocks of variable composition is converted into an essentially homogeneous granite—it is an homogenizing process. It is difficult to see how a zoned pegmatite could be the result of an homogenizing process. The writer has examined a pegmatite near Gunnison, Colorado,[7] containing a relatively thin core-margin zone averaging 10 to 13 percent beryl in crystals up to 28 inches in diameter. Such a concentration of a relatively rare element by a process of granitization is not probable.

The second concept is less extreme. The liquid that forms in advance of the wave of granitization is rich in volatiles and elements that will not fit into the lattice of the normal granite minerals. This liquid is, then, similar to that formed by differentiation of a granite magma, a granitic rest-magma, and it is emplaced by injection. Backlund (3, p. 115) states that this liquid is at low temperature. Granted, for the moment, that this liquid can form in such a way, the injection of a granitic liquid is again being considered, the same pegmatite fluid derived in a different way by the magmatic theory.

There are some points that might be mentioned concerning the formation of this liquid by a granitization process. In addition to the volatiles expelled in advance of granitization, basic elements (Fe, Mg, Ca) must also be eliminated from the granitized rock. These elements are certainly not constituents of pegmatites in any great degree. What is the relation of the expelled basic elements to the granitic liquid? There may also be a problem in the transfer, by solid diffusion, of elements with large ionic radii.

The Palingenesis Theory.—The theory of palingenesis holds that under deep-seated conditions of high temperature and pressure a partial melting of crustal rocks may give rise to a magma. (If a partial remelting takes place the term *anatexis* is applied.) This idea has been called on to explain the origin of intimately penetrating simple quartz-feldspar pegmatites in migmatite zones. The theory falls down when applied to complex pegmatites because it cannot explain the concentration of rare elements found in these pegmatites. In order for a concentration of rare elements to take place, a large quantity of crustal material would have to be melted *and differentiated.*

The theory of palingenesis might be applied in the Mica Mine area. No intrusive body is exposed; the pegmatites are essentially simple quartz-feldspar-

[7] The Field prospect, Quartz Creek area, Gunnison County, Colorado.

mica rocks; pegmatites intimately penetrate the host; *lit-par-lit* zones are present; and augen and stringers of pegmatite occur throughout the host. The bulk of the country rock is of a composition to yield a granite magma on melting (Table 2). One objection to this theory in the Mica Mine area is the tourmaline content of some of the pegmatites. In some pegmatites the tourmaline content may exceed 1 percent. Many crustal rocks contain boron in small amounts, but in order for tourmaline to be concentrated in the amounts found in the Mica Mine pegmatites, a differentiation of the palingenic or anatectic magma must have taken place. If differentiation is allowed, the palingenic theory and the magmatic theory are one and the same.

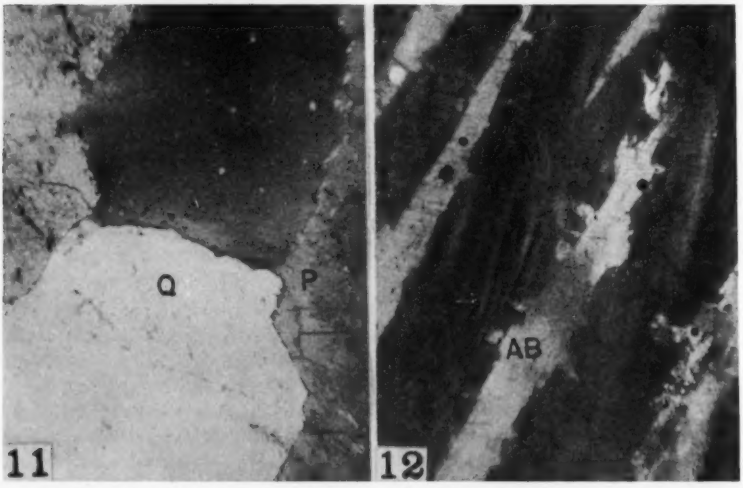


FIG. 11. Quartz veinlet in plagioclase in fine-grained pegmatite. P, plagioclase; Q, quartz. ×75.

FIG. 12. Microcline perthite from the Mica Mine area. M, microcline; AB, albite. ×75.

The Open-System Theory.—The modern open-system theory holds that pegmatites form by crystallization of solutions moving through an open system. Pegmatite units may be formed by progressive filling by solutions changing in composition and/or by replacement (6, 20). There is no general agreement on whether the fluids are attenuated aqueous solutions or magmatic solutions. Andersen (2, p. 32) has suggested that quartz may crystallize from a dilute hydrothermal solution at the relatively cold far end of an opening while quartz and feldspar are crystallizing from a more magmatic solution at the relatively hot end of the same opening.

The general features of pegmatites listed on page 180 can for the most part be explained by the open-system theory. One of the strongest argu-

ments for the theory is that pegmatites have been reportedly traced into quartz veins. See Tolman (23) for a summary of such reports. Against the theory is the fact some pegmatites show evidence of injection, and some pegmatites contain pod-like units completely surrounded by other units. To the writer, however, the picture of "magmatic mother liquors" or "magmatic solutions" moving through channels under pressure and forcing aside the walls is not dissimilar to that of a fluid rest-magma being "injected" in a similar environment. It has been suggested by proponents of the open-system theory that the alleged isolated pods are connected by fine capillary-like channels (2, p. 14).

In the Mica Mine area internal features such as discontinuous cores, interference of schist partitions with zoning, fracture fillings extending from core through wall zone, *localization of contamination by host,* and lack of plagioclase in any of the cores are, in the writer's opinion, more satisfactorily explained by crystallization in a closed rather than open system.

Magmatic Theory.—The thesis of the magmatic theory is that pegmatites result from injection of a granitic rest-magma which, through crystallization in successive stages, produces (if physical conditions during crystallization are favorable) a sequence of mineralogical and textural units. There may be a modification of any of these primary units by still unconsolidated pegmatite fluids within the system or by external hydrothermal solutions in an open system. There is some dissension within the ranks of the magmatists on the importance of this hydrothermal phase. One of the main tenets of the magmatic theory is that pegmatites are emplaced in a closed or restricted system.

In the review of the preceding theories it is seen that the pegmatite source is probably an injectable medium which contains, in some instances, a concentration of rare elements. It must be a solution rich in alkalis and volatiles. Most geologists agree that such a solution is the end-product of a crystallizing, and therefore differentiating, granite magma. It is necessary to have some process of concentration to explain the amount of rare elements in pegmatites no matter how the original solution was derived. The general features of pegmatites listed on page 180 and the features of Mica Mine pegmatites can be satisfactorily explained by the magmatic theory.

Many geologists studying complex pegmatites believe that one or more hydrothermal replacement phases follow the magmatic phase. See Landes (16) for a detailed treatment of this branch of the magmatic theory. In the Mica Mine area only one pegmatite, the Mica Mine No. 1 (Fig. 14), contains a unit that may owe its origin to a later hydrothermal phase. This pegmatite contains a small plagioclase-quartz replacement body that cuts the plagioclase-quartz-perthite-muscovite zone. The Mica Mine area pegmatites are essentially simple quartz-feldspar-muscovite pegmatites, and it is the writer's opinion that they formed in one magmatic phase.

In addition to the concentration of rare elements, pegmatites have many features of texture, form, and relation to host that are not found in the normal intrusive rock. The explanation of these features must come from a study of the nature of the pegmatite fluid during crystallization and the mode and horizon of emplacement of the pegmatite body.

Nature of the Pegmatite Liquid.

Experimental Evidence.—Goransen (8) has shown that under conditions of high pressure a granitic magma can hold as much as 10 percent water. He calculated that at pressure of 5,000 bars (equal to approximately 18 km in depth), the amount of water soluble in the magma is between 9 and 10 percent and that the 10 percent value is approached asymptotically.

Smith (22, p. 545), after a series of experiments, concludes that near the end of magmatic crystallization a water solution is generated which is immiscible with the residual silicate solution. Soluble components are partitioned between the two immiscible liquids. Crystallization of the silicate solution in channels of escape from the magma forms pegmatites, and the crystallization of the water solution in similar channels forms veins containing metallic sulphides. Smith calculated the composition of a residual liquid after 96 percent crystallization of a granitic magma. With 2 percent water in the original magma, the rest-magma contains 20 percent water after 50 percent crystallization, 50 percent water after 96 percent crystallization, and 67 percent water after 97 percent crystallization of the original magma. A sealed bomb was charged with the calculated solution and heated to temperatures as high as 500° C. The temperature was maintained for a specified length of time and the bomb was then chilled. Three phases—crystals, a viscous green silicate liquid, and a water solution—were observed in some instances upon opening the bomb. The temperature range of the three-phase "pegmatitic stage" of Smith (22, p. 543) is 290° to 550°. It should be noted, however, that three phases were observed after cooling the bomb and not at the high temperature. Chilling of the bomb may or may not have preserved the high-temperature relations. Morey (18), in a discussion of Smith's work, says that he can see no experimental evidence that makes probable the formation of two immiscible liquids in water-silicate systems. However, Tuttle and Friedman (25) found two immiscible liquids in the system H_2O–Na_2O–SiO_2. The so-called "heavy phase" found in these experiments was a viscous siliceous liquid immiscible with a second essentially hydrous phase. Equilibrium relations were determined at 250–300–350 degrees C.

Tuttle and Bowen (24) reported that a high and a low temperature form of albite exists and, in the presence of fluxes, the transition between the two forms may take place as low as 700° C. Pegmatite albite is the low-temperature form.

Pegmatite quartz is low quartz with a temperature of formation less than 573° C plus pressure correction, or about 600° C as a round number. Ingerson (12, p. 387), applying the liquid-inclusion method, states that measurements on pegmatite quartz indicate temperatures of formation of less than 250° C.

These various experiments have shown that (1) a substantial amount of water is soluble in a granite magma under pressure, and (2) the temperature of formation of pegmatites is a good deal lower than the 600° C formerly considered a satisfactory figure. The possibility of formation of two immiscible liquids, a water solution and a silicate liquid, in a rest-magma must be considered.

Composition.—Pegmatites are exceedingly variable in composition but nearly all pegmatites are high in potassium, aluminum, sodium, and silicon. With these fundamental pegmatite elements occur variable amounts of calcium, iron, manganese, lithium, beryllium, phosphorus, halogens, boron, uranium, thorium, caesium, cerium, tin, columbium, tantalum, and minor metallic sulphides. Other rare elements are less commonly present. These rarer elements characterize pegmatites of certain districts, but only a very small percentage of pegmatites contain minerals other than quartz, feldspar, and mica. The concentration of these rarer components in the granitic rest-magma depends on their concentration in the original magma. A volatile-rich and alkali-rich rest-magma still appears to be the most likely source of pegmatite fluids. An analysis of a representative sample of pegmatite from the Mica Mine area is shown in Table 2.

Emplacement of the Pegmatites.

Andersen (2, p. 5), in discussing the relation between pegmatites and normal igneous dikes, says: "It is obvious that the igneous dikes have been formed in the upper parts of the Earth's crust, the zone of fracture. At the moment of intrusion the temperature of the surrounding rocks must have been relatively low." This is not a new idea and few geologists will question it. There are a number of points which indicate a different environment for pegmatite emplacement. The intimate penetration of the host rock, irregular forms, coarse uneven texture, and zonal development serve to distinguish pegmatites from igneous dikes. The hypothesis of a relatively deep-seated horizon of emplacement, in some instances concomitant with orogenic stresses, seems to answer many problems.

In a deep-seated environment where pegmatite fluid and host rock are at approximately the same temperature, no chilling and resulting precipitate crystallization would be expected. With evenly-maintained temperature and injection pressures and an almost unlimited time factor, the low viscosity of the pegmatite fluid would facilitate an intimate penetration of the host. Injection pressures would not be suddenly released through open fractures. The injection, although considered a one-pulse mechanism, would be a slow process involving a variable amount of digestion of the host and dilation. Andersen (2, p. 13) suggests that lens-shaped openings may have been created by orogenic forces as well as by pressure of the pegmatite fluid. This is in harmony with the theory that intimately penetrating pegmatites are a feature of larger synkinematic intrusions. The irregular form of some pegmatites is not difficult to envisage under the deep-seated conditions just pictured. Graton (9, p. 36) explains the irregular form of pegmatites in the metamorphic rocks of the southern Appalachians by reference to the nature of failure of the host rock under stress. He says: "It thus appears that the directions or the loci of greatest weakness—those places which would determine the position and form of the intrusion—are not simple planes, but are instead comprised of series of parallel planes of irregular extent, arranged more or less step-wise, in some places branching, in others overlapping, and in still others almost separated by

the intervention of localities where the rock is stronger; i.e., of greater cohesion between the two walls of the plane of movement."

In discussing "miniature pegmatites," Andersen (2, p. 12) says that siliceous solutions rich in the constituents of potassium feldspar penetrate the foliated rocks wherever they find suitable openings, forming in some places little lenses, eyes, and streaks, and in other places larger bodies. These solutions, says Andersen, acted in part by replacement and in part by pushing the containing rocks aside. If digestion (replacement in a closed system) is substituted for replacement, this statement applies to the Mica Mine area.

In the Mica Mine area the emplacement of the pegmatites was accomplished in part by forcing aside the host rock, dilation, and in part by digestion of the host rock. Both processes were facilitated by the ease of penetration along foliation in the more schistose rocks.

Crystallization.

In a deep-seated environment the emplacement of pegmatites would cause the collection of diffused elements in large crystals as the result of: (a) a very slow and prolonged period of crystallization and/or (b) low viscosity of the crystallizing fluid. The occurrence of a gigantic single crystal of beryl, for example, is known. This amounts to a single center of crystallization in a system maintained in that precarious balance until diffusion of large quantities of beryllium to that center could take place. This, of course, is an extreme example. However, the solubility relations of the various pegmatite constituents must be maintained in delicate balance to explain zoning and coarse textures. A high concentration of a given substance also tends to increase crystal size. The number of centers of crystallization in the system must have been limited in contrast to normal igneous rocks.

Order of Crystallization.—The sequence of crystallization in the Mica Mine area results from a crystallizing liquid containing a large excess of potash. The solubility product for potassium feldspar was exceeded early in the cooling history, giving rise to large crystals of microcline perthite around a relatively few centers. The fine-grained matrix represents a later period of crystallization. Small microcline perthite crystals, plagioclase, quartz, and muscovite characterize this assemblage. If any of the perthite formed by replacement by albite along fracture planes within microcline, rather than by exsolution, it probably formed during this period of crystallization. Microcline in the wall zone and in schist inclusions undergoing digestion was corroded and embayed by plagioclase and by quartz. The potash released probably migrated into the uncrystallized part of the pegmatite and was used later in the growth of the larger microcline perthite crystals in the core.

Crystallization of the wall zone exhausted the soda and lime content of the pegmatite liquid and left a highly siliceous residue rich in potash and containing the boron and iron necessary for the formation of tourmaline. This liquid, or parts of this liquid, filled fractures in and sought out planes of entry to the crystallized wall zone. Quartz-tourmaline stringers and quartz-perthite-

tourmaline-muscovite fracture fillings formed during this period. The secondary muscovite found along crystal boundaries and in cracks also probably formed at this time. Final consolidation produced a coarse quartz-microcline perthite core containing minor muscovite. If partitions of country rock interfered with crystallization of the pegmatite as a unit, a number of coarse, perthite-quartz segregations formed instead of a single core.

Source of the Plagioclase in the Mica Mine Area.—A number of points lead the writer to consider the plagioclase of the wall zone as material crystallized from the original injection of liquid and not added by hydrothermal solutions. They are as follows:

(1) The anorthite content of plagioclase from pegmatites in contact with amphibolite is definitely influenced by the amphibolites and reflects digestion of the amphibolite.
(2) The anorthite content of the plagioclase in the pegmatites changes progressively from north to south showing a definite, though undetermined, pattern. The plagioclase of the northern part of the area is oligoclase, not a common hydrothermal mineral.
(3) The plagioclase-bearing wall zone is symmetrical about a core that does not contain plagioclase. Why a later hydrothermal plagioclase should respect earlier primary boundaries and reflect the shape of the pegmatite body is difficult to understand.
(4) The plagioclase of the wall zone is cut by later quartz-tourmaline stringers emanating from the core.
(5) The microcline in the wall rocks does not show evidence of albitization.

Problem of the Quartz Core.—The presence of a pure quartz core in a pegmatite has sometimes been considered as a point against the magmatic theory. Progressive crystallization should leave a quartz magma or pure quartz melt which, because of the extreme temperature necessary to maintain such a melt, appears impossible. Jahns (13) discusses this problem and concludes that this quartz represents a late-magmatic stage where temperatures did not exceed 300° C. Jahns says that this *magma-like* (writer's italics) solution rich in SiO_2 could exist at such temperatures, provided that substantial amounts of alkalis were present. This is in accord with the evidence of the quartz-perthite cores of the Mica Mine area. The quartz-tourmaline stringers and the fracture fillings extending from the core indicate that this residuum was a very mobile fluid and certainly not a highly viscous melt.

One can only speculate on the nature of the solution giving rise to the quartz core. Apparently it is not a magma and not a dilute hydrothermal solution but a relatively low temperature siliceous liquid somewhere in between. Present experimental evidence does not indicate the existence of such a liquid unless it is represented by Smith's (22) silicate solution or the heavy immiscible phase of Tuttle and Friedman (25).

CONCLUSIONS ON ORIGIN OF PEGMATITES OF THE MICA MINE AREA.

(1) The formation of pegmatites by crystallization of a siliceous, alkali-rich, volatile-rich rest-magma in an essentially closed or restricted system is the most satisfactory explanation of the major features of pegmatites.

(2) Local palingenesis or anatexis cannot explain the concentration of rare elements found in some pegmatites. In order to account for the amount of rare elements in some pegmatites some process of concentration is necessary. The rest-magma may have been formed by: (a) Crystallization (and resulting differentiation) of an original granitic magma; (b) crystallization (and resulting differentiation) of a granitic magma formed by wholesale palingenesis or anatexis of a large mass of crustal rocks; (c) production of a fluid rich in volatiles and expelled elements in advance of a wave of granitization. The product of these three processes would be similar and it is not possible to determine the process from the crystallized product.

(3) The hypothesis of formation of pegmatites by metasomatic replacement of host rocks is not satisfactory in the light of information on the internal features of pegmatites.

(4) Pegmatites are emplaced in a deep-seated environment, perhaps under orogenic stresses, by a combination of dilation and digestion. The relative importance of the two processes varies widely in different districts. The process of entry of the pegmatite fluid is one of injection under conditions of sustained heat and pressure. There was little thermal contrast between pegmatite-

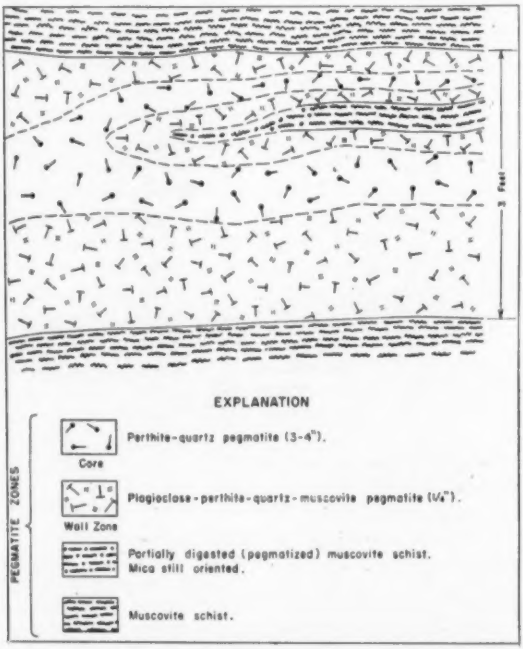


FIG. 13. Idealized section showing perthite-quartz core split by schist partition. Schist partition grades into pegmatite.

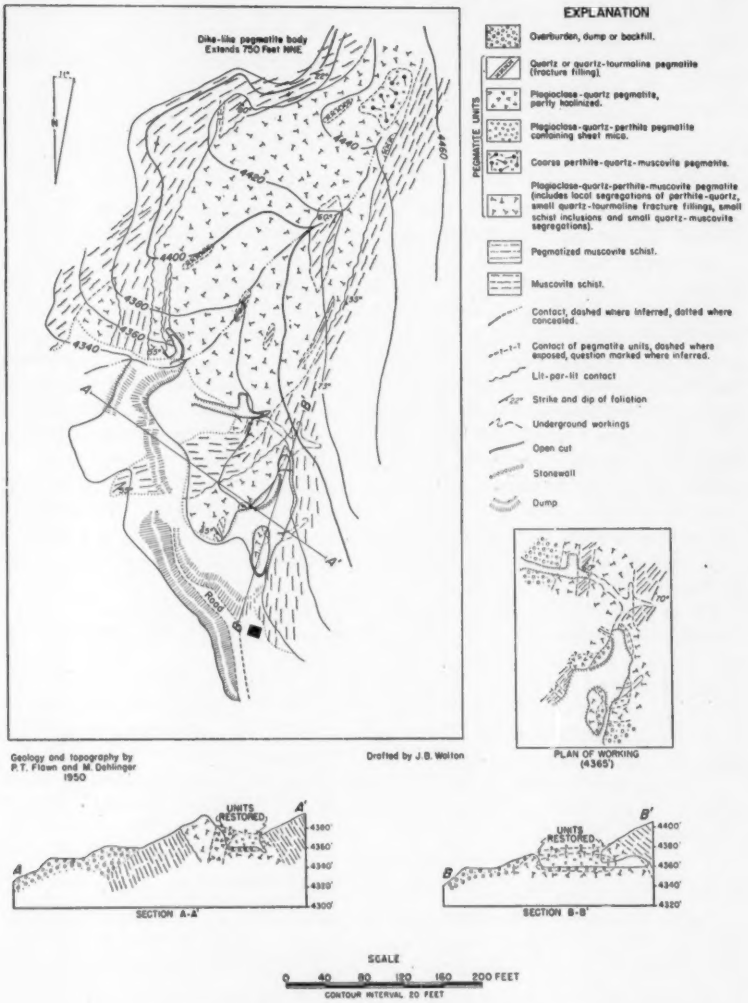

Dike-like pegmatite body
Extends 750 Feet NNE
EXPLANATION
PEGMATITE UNITS
Overburden, dump or backfill.
Quartz or quartz-tourmaline pegmatite (fracture filling).
Plagioclase-quartz pegmatite, partly kaolinized.
Plagioclase-quartz-perthite pegmatite containing sheet mica.
Coarse perthite-quartz-muscovite pegmatite.
Plagioclase-quartz-perthite-muscovite pegmatite (includes local segregations of perthite-quartz, small quartz-tourmaline fracture fillings, small schist inclusions and small quartz-muscovite segregations).
Pegmatized muscovite schist.
Muscovite schist.
Contact, dashed where inferred, dotted where concealed.
Contact of pegmatite units, dashed where exposed, question marked where inferred.
Lit-par-lit contact
Strike and dip of foliation
Underground workings
Open cut
Stonewall
Dump
Road
Geology and topography by P.T. Flawn and M. Oehlinger 1950
Drafted by J.B. Walton
PLAN OF WORKING (4365')
UNITS RESTORED
SECTION A-A'
SECTION B-B'
SCALE
0 40 80 120 160 200 FEET
CONTOUR INTERVAL 20 FEET

FIG. 14. Geologic map of Mica Mine No. 1.

forming solution and host. The low viscosity of the pegmatite fluid under such conditions and with an almost unlimited time factor would facilitate intimate penetration of the host rock.

(5) Physical conditions maintained in a deep-seated environment during crystallization are such as to produce a delicate balance of solubility factors,

limiting the number of centers of crystallization and producing pegmatite textures and zonal features.

(6) A later hydrothermal phase, although important in some districts, is not present in the Mica Mine area.

ECONOMIC POSSIBILITIES.

General Remarks.

The first organized attempt to develop the Mica Mine area began in 1920 with the formation of the Micolithic Company of Texas, a stock company with a very large capitalization. The purpose of this company was to develop a product for facing cutstone. The installations established by this company were impressive. They consisted of a large steel-framed mill and warehouse, 5 miles of railroad linking the mica mine with the Southern Pacific Railroad, a Fairbanks Morse diesel electric power plant (240 volt), a number of dwelling houses, and a pipe line and pump house connecting the mine with a well in the bolsom. At this time the Mica Mine rivaled the town of Van Horn in size. The only traces of the actual quarrying operations conducted by this company, strangely enough, are a few small pits in the schist.

The Micolithic Company went bankrupt in 1930, and its assets were taken over by the Rio Grande Quarries Company. The property and assets of this company were in turn sold, in 1940, to the present owners, a syndicate composed of twelve members, represented by Mr. M. A. Baldwin and Dr. W. H. Scherer of Houston, Texas.

During the war the property was leased to the Texas Mica and Feldspar Company which operated it for a short time. The lessees hoped to take advantage of the Government subsidy on sheet mica. It was during this period of operation that the U. S. Bureau of Mines conducted exploration and testing (11). The writer is informed by Mr. H. O. DeBeck of the Research Laboratory in Ceramics, The University of Texas, that about $5,000 worth of mica was sold as "strategic mica" during this period.

The present workings consist of two short adits in the pegmatite opposite the mill (Figs. 2, 14) and a number of small cuts in other pegmatites. Small stock piles of feldspar are found near some of the cuts.

Possibilities for Development.

Mica.—In spite of the name, the area has no future in production of sheet mica or of scrap and sheet mica as a *primary* product unless there is a marked price increase. Some of the pegmatites will yield an average of 5 to 8 percent scrap mica recovery from a process separating run-of-the-mine pegmatite for feldspar. This scrap mica would be an important by-product. A good grade of "electrical" mica occurs in the pegmatites in the immediate vicinity of the mill. The existence of any sizable reserve of this "electrical" mica remains to be proved. A very small amount, too small for economic production, was classed as "strategic" during the war. The results of power factor and flotation tests run by the Bureau of Mines are given by Holt and Bowsher (11).

Feldspar.—There is a considerable tonnage of feldspar in the Mica Mine area. The average pegmatite consists of 30 to 40 percent easily-cobbed potash spar, and a number of pegmatites are large enough for quarrying operations. Should it prove feasible to mill and float run-of-the-mine pegmatite, a scrap mica and perhaps a clean quartz tailing would be salable in addition to the spar. Black tourmaline is the only deleterious constituent of the pegmatite and should be easily separated.

The important point for investigation is the iron content of the feldspar. The Bureau of Mines (11, p. 7) found 0.28 percent Fe_2O_3 in a minus 20-mesh flotation concentrate, of which feldspar made up 51.8 percent of the product (7.4 percent mica, 32.2 percent quartz, 8.5 percent slime). It should be noted that these tests were run on mill tailings, and it was not specified from which pegmatite these tailings were derived. If the iron content of the feldspar has any relation to the color of the feldspar it must be extremely variable throughout the area. It will be necessary to determine the iron content of the feldspar from individual pegmatites and this will entail systematic sampling. The University of Texas Bureau of Economic Geology plans to carry out additional metallurgical testing on the feldspar of the Mica Mine area.

Advantages and Disadvantages of the Area.—The advantages of the Mica Mine area are proximity to a railroad, abundant Latin-American labor, and installations already at hand.

An adequate water supply may constitute a problem. Water may be produced from the basin fill and pumped to the mine area. The fault zone along the west front of the range should be explored for water.

The specifications of the feldspar product may be different from that now in use in Texas industry. The feldspar industry is a "closed industry" in the sense that a consumer may be forced to change his plant in order to change his source of feldspar and thus must be assured of supply before making such a change.

BUREAU OF ECONOMIC GEOLOGY,
UNIVERSITY OF TEXAS,
AUSTIN, TEXAS,
Oct. 30, 1950.

BIBLIOGRAPHY.

1. Andersen, Olaf, The genesis of some types of feldspar from granite pegmatites: Norsk geol. tidsskr., vol. 10, pp. 116–207, 1928.
2. ——, Discussion of certain phases of the genesis of pegmatites: Norsk geol. tidsskr., vol. 12, pp. 1–55, 1931.
3. Backlund, H. G., The granitization problem: Geol. Mag., vol. 83, pp. 105–117, 1946.
4. Baker, C. L., Exploratory geology of a part of southwestern Trans-Pecos Texas: Texas Univ. Bull. 2745, 70 pp. and map, 1927.
5. Cameron, E. N., Jahns, R. H., McNair, A. H., and Page, L. R., Internal structure of granitic pegmatites, Econ. Geol. Pub. Co. Mon. II, 112 pp., 1949.
6. De Almeida, S. C., Johnston, W. D., et al., The beryl-tantalite-cassiterite pegmatites of Paraiba and Rio Grande do Norte, northeastern Brazil: ECON. GEOL., vol. 39, pp. 206–223, 1944.
7. De Lapparent, Jacques, Leçons de pétrographie, Masson et Cie., Paris, p. 151, 1923.
8. Goransen, R. W., The solubility of water in granite magmas: Am. Jour. Sci., 5th ser., vol. 22, pp. 481–502, 1931.

9. Graton, L. C., Gold and tin deposits of the southern Appalachians: U. S. Geol. Survey Bull. 293, 134 pp., 1906.
10. Higazy, R. A., Petrogenesis of perthite pegmatites in the Black Hills, South Dakota: Jour. Geology, vol. 57, pp. 555–581, 1949.
11. Holt, S. P., and Bowsher, J. A., Texas Mica and Feldspar Company, Culberson and Hudspeth counties, Texas: U. S. Bur. Mines Rept. Inv. 4009, 7 pp., 1947.
12. Ingerson, Earl, Liquid inclusions in geologic thermometry: Am. Mineralogist, vol. 32, pp. 375–388, 1947.
13. Jahns, R. A., Masses of pegmatite quartz (abst.): Geol. Soc. America Bull., vol. 59, p. 1374, 1948.
14. Johannsen, A., Descriptive petrography of the igneous rocks, Vol. II, University of Chicago Press, pp. 72–84, 1932.
15. King, B. C., The form and structural features of aplite and pegmatite dikes and veins in the Osi area of the northern provinces of Nigeria and the criteria that indicate a non-dilational mode of emplacement: Jour. Geology, vol. 56, pp. 459–475, 1948.
16. Landes, K. K., Origin and classification of pegmatites: Am. Mineralogist, vol. 18, pp. 33–56, 1933.
17. Lonsdale, J. T., Igneous rocks of the Terlingua-Solitario region, Texas: Geol. Soc. America Bull., vol. 51, pp. 1539–1626, 1940.
18. Morey, G. W., Transport and deposition of the non-sulphide vein minerals. III. Phase relations at the pegmatitic stage (discussion and communications): Econ. Geol., vol. 44, pp. 151–154, 1949.
19. Perrin, R., and Roubault, M., On the granite problem: Jour. Geology, vol. 57, pp. 357–379, 1949.
20. Quirke, T. T., and Kremers, H. E., Pegmatite crystallization: Am. Minerologist, vol. 28, pp. 571–580, 1943.
21. Redfield, R. C., Mica in Texas: Texas Univ. Pub. 4301, p. 429, 1943.
22. Smith, F. G., Transport and deposition of the non-sulphide vein minerals. III. Phase relations at the pegmatitic stage: Econ. Geol., vol. 43, pp. 535–546, 1948.
23. Tolman, Carl, Quartz dikes: Am. Mineralogist, vol. 16, pp. 278–299, 1931.
24. Tuttle, O. F., and Bowen, N. L., High temperature albite (abst.): Geol. Soc. America Bull., vol. 60, p. 1925, 1949.
25. Tuttle, O. F., and Friedman, I., Liquid immiscibility in the system H_2O–Na_2O–SiO_2: Am. Chem. Soc. Jour., vol. 70, pp. 919–926, 1948.
26. Von Streeruwitz, W. H., Report on the geology and mineral resources of Trans-Pecos Texas: Texas Geol. Survey 2d Ann. Rept. (1890), pp. 665–738, 1891.
27. ——, Report on the geology and mineral resources of Trans-Pecos Texas: Texas Geol. Survey 4th Ann. Rept. (1892), pp. 141–175, 1893.

ORIGIN AND SALINITY DISTRIBUTION OF ARTESIAN WATER IN THE ADELAIDE PLAINS, SOUTH AUSTRALIA.[1]

KEITH R. MILES.

CONTENTS.

	PAGE
Abstract	193
Introduction	193
Climate	194
Physiography and geology	194
The aquifers	197
Origin of the water	199
The intake areas	199
Movement of the underground water	200
Fluctuations of level	200
Composition of waters	200
Distribution	202
Intake and discharge	205
Conclusions	206

ABSTRACT.

The Adelaide Plains comprise a narrow strip of lowland lying between the Mt. Lofty Ranges and the sea. The plain is built up of Recent-Pleistocene alluvials, overlying Pliocene and Miocene marine sediments and Oligocene (?) freshwater alluvials, which in turn lie upon Precambrian bedrock. The flanking hills were formed by Plio-Pleistocene block faulting.

Artesian and subartesian water is met with in the Tertiary marine beds. Recent investigations have revealed two small basins near Adelaide where fresh artesian water occurs surrounded by areas containing water high in connate salts. This fresh water comes from small water courses draining the highland to the east. It enters the artesian aquifers by moving down the Para Fault. Studies to date have been sufficient to indicate that the distribution of fresh water is restricted within clearly delineated boundaries and the supplies available are probably strictly limited, though adequate for all present seasonal demands. Local overpumping, however, could well result in a reduction in areas over which fresh water is available for development.

INTRODUCTION.

THE city of Adelaide, capital of the State of South Australia, lies at the southernmost end of a long narrow, flat plain, which is flanked on the west for most of its length by the sea (Gulf St. Vincent) and on the east by the Mt. Lofty Ranges. This plain extends northwards from just below Adelaide to past the head of Gulf St. Vincent and on as a narrow strip of undulating low land for a further 40 miles (Fig. 1). It has a total length of about 100 miles and ranges

[1] Published by permission of the Director, Geological Survey of South Australia.

in width from less than 10 miles up to 25 miles, and has a total area of over 1,500 square miles. Artesian or subartesian water has been found over most of this plains area which is known as the Adelaide Plains Artesian Basin.[2]

The Adelaide Plains have a general elevation of between 50 and 100 feet above sea level, the flanking highland averaging about 1,000 feet above sea level and rising to a maximum at Mt. Lofty (2,384 ft.) immediately east of Adelaide.

The region which has been the subject of recent hydrologic investigations [3] is shown in Figure 1. It has a total area of 276 miles and comprises the southernmost lobe of the Adelaide Plains Artesian Basin. It encompasses the entire city and suburban areas of Adelaide and Port Adelaide (population 401,000), the most closely settled and industrialized centers in South Australia. Outside of these areas the land is devoted principally to agriculture. Underground water is freely used over much of the region for irrigation of market gardens, vineyards and orchards, and for stock, and to a lesser extent for secondary industries and to water parks, gardens, and playing fields within the metropolitan area.

In addition, water from the artesian and subartesian aquifers in this region has been utilized on a number of occasions to augment the city's water supply. Since July, 1945, some 40 wells have been drilled and brought into production by the Department of Mines of South Australia, and are being held as an emergency source of water supply. Much valuable geologic and hydrologic data have been obtained during the course of these drillings and from subsequent observations. This information has formed the basis for a recent general study of hydrologic conditions in the area and an investigation into the origin and salinity distribution, and the future development of the artesian waters.

CLIMATE.

The Adelaide Plains experiences a Mediterranean type of climate—cool, wet winter, and warm to hot, dry summer. Average rainfall ranges from about 17 inches at the coast to 25 inches in the foothills, and for Adelaide 21.1 inches. Rainfall increases rapidly in the highland to the east, reaching a maximum of 47 inches at Mt. Lofty. Average annual evaporation at Adelaide is over 56 inches.

PHYSIOGRAPHY AND GEOLOGY.

The Adelaide Plains shelf and the adjoining highland were formed in geologically recent times (late Pliocene to Pleistocene) as a result of block faulting movements relieving differential crustal stresses developed in the area. These movements resulted in the sinking of a wide block which has now become the Adelaide Plains; the formation of Gulf St. Vincent by further down faulting to the westward; and to the east the relative uplift of several blocks

[2] Ward, L. K., The occurrence, composition, testing and utilization of underground water in South Australia and the search for further supplies: South Australia Geol. Survey Bull. 23, pp. 78–86, 1946.

[3] Miles, K. R., Geology and underground water resources of the Adelaide Plains Area: South Australia Geol. Survey Bull. 27, 1950. (In press.)

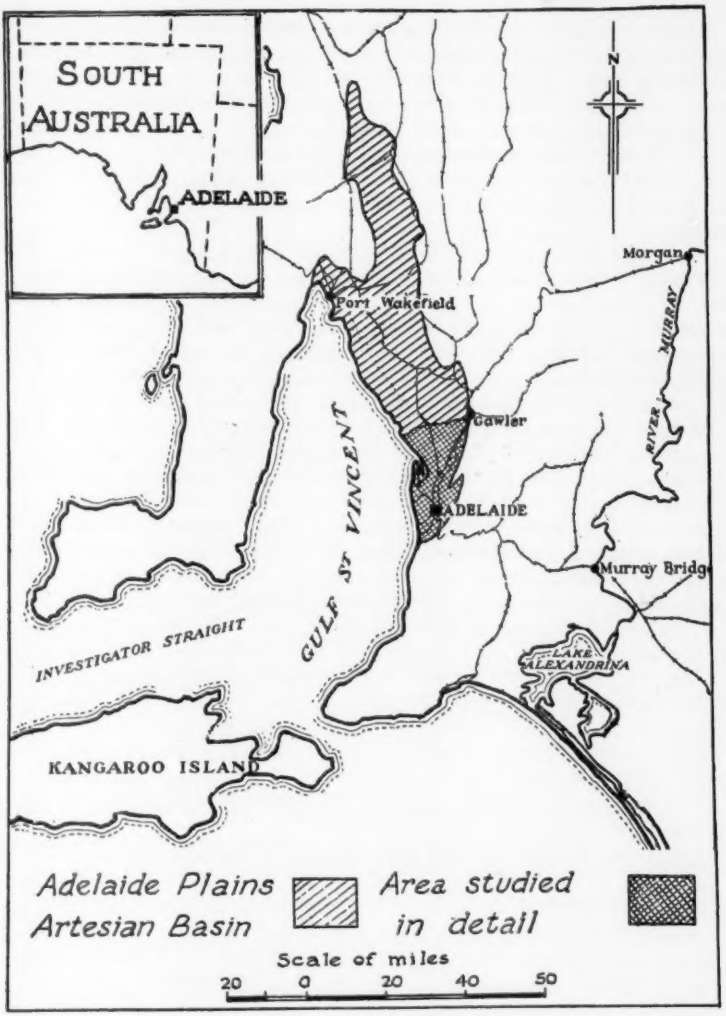


FIG. 1. Locality plan, showing the Adelaide Plains artesian basin, and the area discussed in this paper.

which now constitute the Mt. Lofty Ranges. These blocks are bounded by sharply defined fault planes, and form fault scarps.[4]

The first of these, the Para Fault, runs southerly from Gawler to the western edge of Adelaide city block and thence in a curved line south-westerly to westerly, to meet the coast somewhere just north of Glenelg. Owing to a regional southward or south-eastward tilt, the Para Block plunges under the plain level south-west of Adelaide and no trace of the Para scarp is visible on the surface. Other important faults are the Burnside Fault, making a low topographic feature in the foothills to the southeast and east of Adelaide, and the Eden Fault which forms the principal scarp face of the Mt. Lofty Ranges in this region.

Principal surface geological features on the plains themselves from the coast line eastwards are: a narrow belt of calcareous sand dunes fringing the coastline and extending over most of Lefevre Peninsula north of Port Adelaide; a broad strip of estuarine low land lying immediately east of the coastal dunes, and comprising the lower deltaic flood plains of the rivers Sturt, Torrens, Little Para and Gawler—the principal streams which cross the plains and reach the sea; a discontinuous narrow belt of older sand dunes running from east of Glenelg to Port Adelaide, and marking the old eastern shore line of a Recent transgression of the sea; an upper deltaic plain, a broad flat or very gently sloping area of Recent-Pleistocene alluvial clays and sandy clays deposited in the fan deltas of the early Sturt, Torrens, Dry Creek, Little Para and Gawler Rivers, and comprising much of the built-up areas of Adelaide and its suburbs, and the greater part of the agricultural land to the northward; and a narrow foothills outwash apron or piedmont, sloping land consisting of clays, sands and boulders extending along the feet of the flanking highland scarps.

All streams entering the Adelaide Plains rise in the Mt. Lofty Ranges to the eastward. All principal streams, viz. the Gawler River, the Little Para, Torrens and Sturt Rivers, emerge from the highland through steeply graded, topographically youthful, gorge-like valleys. They traverse the plains in meandrine canal-like channels flanked by natural levees, the accumulated products of their own flood plains. Numerous small intermittent flowing streams have cut deeply into the fault scarp faces in places. Most of these creeks disappear into the sediments of their own alluvial fans within the outwash apron belt of the foothills.

Total area drained by these water-courses which feed into the Adelaide Plains Area is about 690 square miles. Gross mean annual runoff is about 31,300 million gallons.

The Adelaide Plains area is built up of at least five different ages of rocks and deposits—Recent-Pleistocene alluvials, including some Recent marines; Pliocene marine; Miocene marine; pre-Miocene (Oligocene?) lacustrine and alluvials; and Precambrian bedrock.

[4] Fenner, C., Adelaide, South Australia—a study in human geography: Roy. Soc. South Australia Trans., vol. 51, pp. 193–256, 1927.
Sprigg, R. C., Some aspects of the geomorphology of the Mt. Lofty Ranges: Roy. Soc. South Australia Trans., vol. 69 (2), pp. 277–302, 1945.

The Recent-Pleistocene deposits cover the greater part of the plains. The formation ranges from less than 20 feet up to 400 feet thick and overlies the Tertiary marine beds with marked unconformity.

Pliocene and Miocene marine formations do not outcrop, though shell-bearing Pliocene limestone is known to occur under very shallow cover in the south bank of the Torrens, in the city area. To the west of Adelaide the Pliocene and Miocene formations on the Adelaide Plains Block are tilted conformably to the southward. The Pliocene has a maximum thickness of about 200 feet to the west of Adelaide. In the north between the Little Para and the Gawler River it thins off and wedges out, while to the south it ends abruptly against the Para Fault where the fault plane curves to the southwest from Adelaide (Fig. 2). South of the fault the Recent-Pleistocene formation, less than 150 thick, lies directly on Miocene marine beds. The Miocene has a maximum known thickness of over 1,150 feet.

Pre-Miocene (Oligocene?) lacustrine and terrestrial deposits are known to underlie the Miocene at considerable depths to the west of Adelaide where they have a thickness of 480 feet, and at shallow depths (less than 80 feet) in the Torrens Valley northeast of Adelaide. Along the eastern foothills they occur directly under Recent outwash alluvium and in places on the Para Block northeast of Adelaide they outcrop or lie under only a foot or so of Recent deposits. They always rest directly upon basement bedrock.

Precambrian bedrock outcrops in the highland fault scarps and at localities along the Torrens bank northeast of Adelaide. It occurs at shallow depths (under 200 feet), usually overlain by Oligocene? in the north eastern suburbs.

THE AQUIFERS.

Underground water occurs in each of the five formations mentioned above. In the Recent-Pleistocene alluvials waterbearing sands and gravel beds, commonly lenticular and discontinuous, from a few feet up to more than 20 feet in thickness, occur interbedded with impermeable clays at various depths from less than 50 feet up to 300 feet in places (Fig. 3). These aquifers have been exploited by many shallow bores or wells fitted with pumps driven by either windmills, electric motors or petrol engines. In the rural districts north of the metropolitan area over 450 wells yield from a few hundred up to a thousand gallons per hour. In the metropolitan area over 200 market gardeners draw water from shallow wells yielding from 2,000 gallons per hour up to 15,000 gallons per hour. About the same number of bores in suburban areas draw shallow ground water from Recent-Pleistocene deposits at the rate of a few hundred gallons per day.

Marine Pliocene and Miocene beds are all fairly permeable and over much of the Adelaide Plains west of the city yield artesian or subartesian water. They consist of calcareous sandstones, limestones, marls, light or dark gray to yellowish white in color. Supplies ranging from 5,000 to 20,000 gallons per hour are pumped from wells sunk into the more permeable zones—coarse shell-rich layers—in these marine series. Between 150 and 180 such wells are at

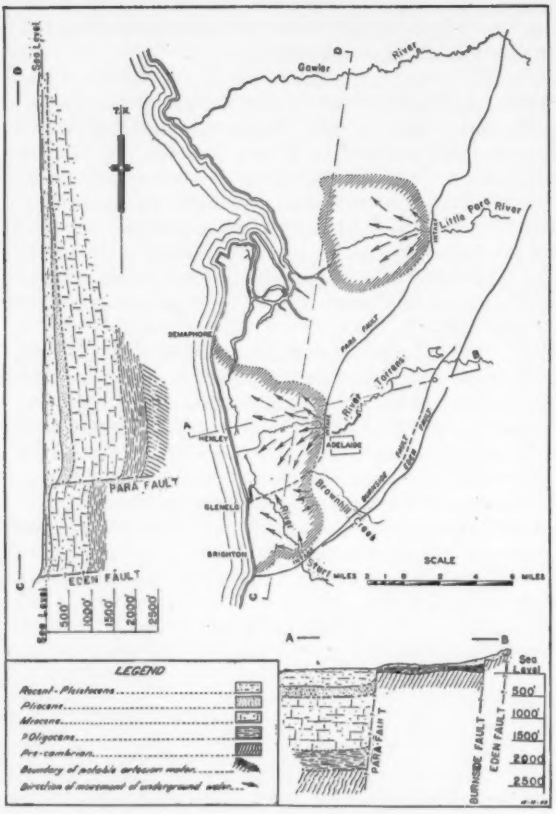


FIG. 2. Plan and geological sections, Adelaide Plains, showing the intakes and direction of underground water movement in areas of potable artesian water (containing less than 1,450 parts per million total salts).

present in part-time operation, supplying water for irrigation, domestic, and industrial needs.

Some ground water is obtained in the pre-Miocene lacustrine sands along the foothills suburbs to the east and northeast of Adelaide, but these sands are often too fine to be very permeable and wells yield supplies seldom exceeding 3,000 gallons per hour of frequently indifferent quality water.

Precambrian bedrock consists mainly of calcareous slates, phyllites and quartzites, mostly dense and impermeable but carrying ground water stored in cracks, fissures and other openings. Wells into bedrock at shallow depths

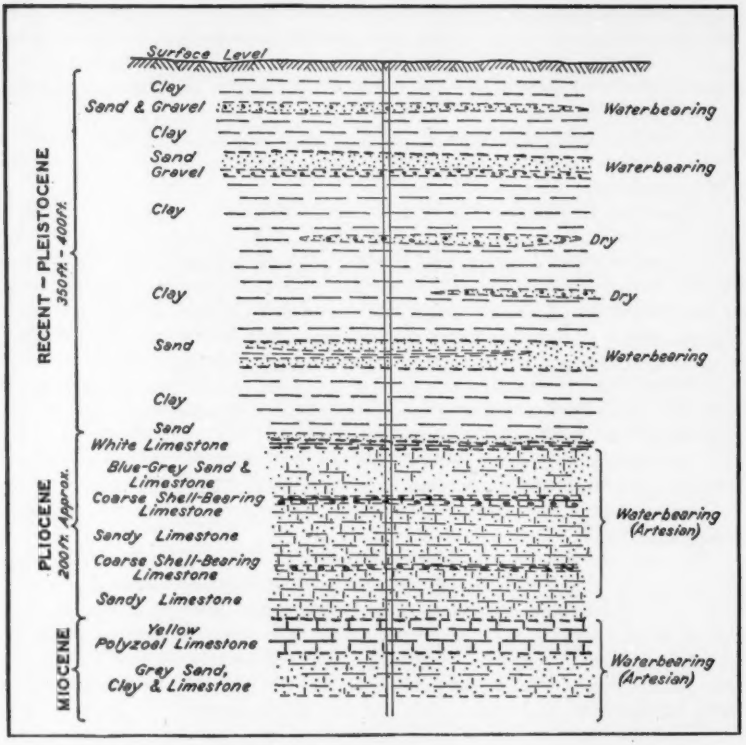


FIG. 3. Diagrammatic geological section showing the aquifers of the Adelaide Plains.

(less than 200 feet) in the Torrens valley and the northeastern suburbs yield supplies averaging 1,500–2,000 gallons per hour.

ORIGIN OF THE WATER.

The Intake Areas.—The source of the great bulk of underground water, both ground water and artesian water, is the rainfall runoff draining from the highland to the east and entering the plains by means of the various streams, creeks, and gullies. This has been adequately demonstrated by plotting the salinity distribution for underground waters at various depths.

The intake areas for the shallower ground waters are mostly in the foothills areas along the paths of the various scarp face tributaries of the Torrens and Sturt rivers, and along the Little Para and Gawler rivers.

On the other hand it has been shown that two major areas of potable water in the artesian basin on the western and southwestern sides of Adelaide derive the bulk of their water by downflow from the Torrens where it crosses the Para Fault immediately west of the city and to a much lesser extent from the Sturt and Brownhill Creek.

A smaller subartesian area in the Parafield-Salisbury district is fed in a similar manner by percolation down the Para Fault where it is crossed by the Little Para River.

Thus it can be said that there are two well defined freshwater basins within the main artesian basin near Adelaide (Fig. 2).

Movement of the Underground Water.—The underground water is moving steadily from areas of high level or potential (the intake areas) towards points of lower potential. The shallow ground waters of the eastern suburbs are flowing westwards to the Para Fault and in some cases thence moving down the fault to enter the subartesian aquifers on the western side of the city.

Within this western area the general movement of the subartesian water is north-northwesterly to westerly, except where reversed near a cone of depression formed by local heavy pumping.

Ultimate discharge of all underground water is probably into the sea, either through shallow submarine gravels, or in the case of the subartesian water by upward movement into the sea floor, along the western edge of the Adelaide Plains fault block.

Fluctuations of Level.—The levels of underground water, both the shallow ground water table and the hydraulic surface of artesian or subartesian water, in any part of the Adelaide Plains are varying continuously. In case of shallow ground waters fluctuations in water table have been demonstrated to be broadly seasonal and due to a number of causes. These include variations in relative rates of recharge by rainfall, stream flow, and of discharge due to pumping from wells, transpiration and evaporation, and natural drainage.

Major fluctuations in hydraulic surface level of pressure waters from Pliocene and Miocene aquifers west and southwest of Adelaide are strongly seasonal in character, showing a decline in summer and recovery in winter (Figs. 4, 5). These are caused by a well marked seasonal pumping discharge from the artesian basin by wells used for irrigation purposes. Maximum variation in level is about 30 feet at Fulham near the coast and minimum (less than 5 feet) in the southwestern suburbs, and at the intake area immediately west of Adelaide. The order of this seasonal variation is illustrated in the hydrographs of typical observation wells (Fig. 6).

The general level of the hydraulic surface over the Torrens-Sturt area of the artesian basin is steadily declining. Over the last 30–40 years it has been lowered between 20 and 30 feet. Observations over the last 12 years indicate that at the present rate of pumping (1,000–1,200 million gallons per annum) the level is falling at the rate of 3–4 inches per annum near the coast, up to about 1 foot per annum near the main intake area west of the city.

Composition of Waters.—The salinity of underground water in the Adelaide Plains varies considerably both in different aquifers and in different parts

of the same aquifer. It ranges from good quality potable waters containing less than 570 parts per million total salts, up to extremely saline waters carrying over 71,500 parts per million and completely useless for exploitation. The predominant salt in all waters is sodium chloride.

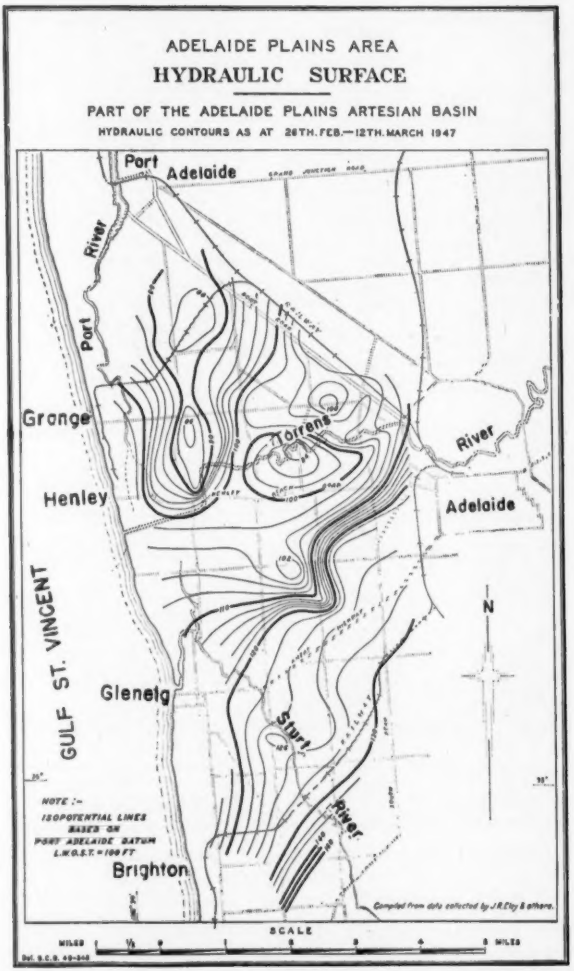


FIG. 4. Hydraulic surface of artesian water west of Adelaide at midsummer (Feb.-March) 1947.

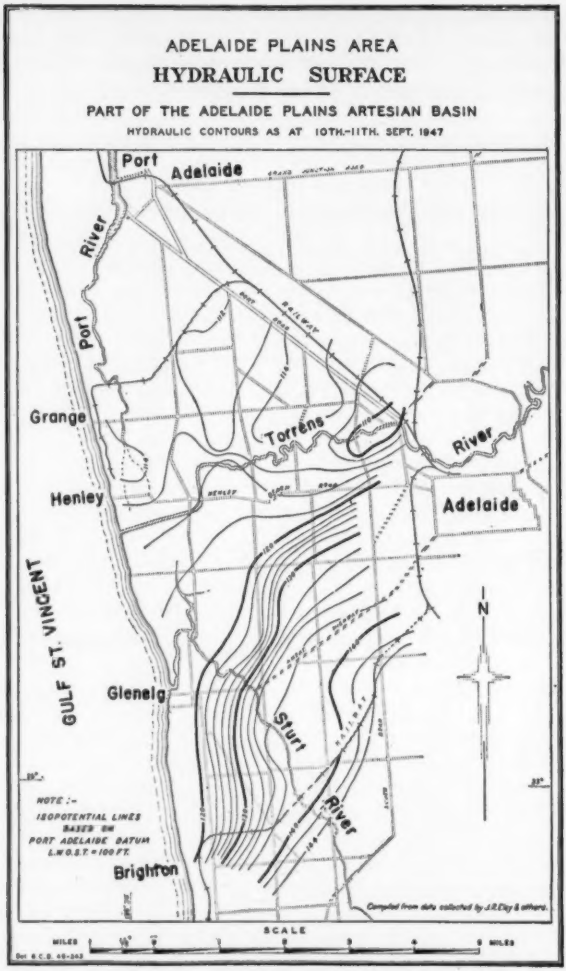


FIG. 5. Hydraulic surface of artesian water west of Adelaide at midwinter (September) 1947.

In general, the very saline waters are rather shallow and confined to localities adjacent to present day or recent estuarine areas. Some typical variations in salinity of waters from different depths are indicated in Table 1.

Distribution.—Distribution of the better quality waters, both shallow

ground waters and deeper subartesian or artesian waters, shows a close relation to proximity of intake areas, to quantity of water passing and to its rate of passage through the aquifers, i.e. to the permeability of the aquifers. On entering the aquifers at the intake areas the water, being meteoric in origin, mostly has a low initial salinity, but it gradually picks up soluble connate salts from the beds through which it passes. Where large quantities of water have

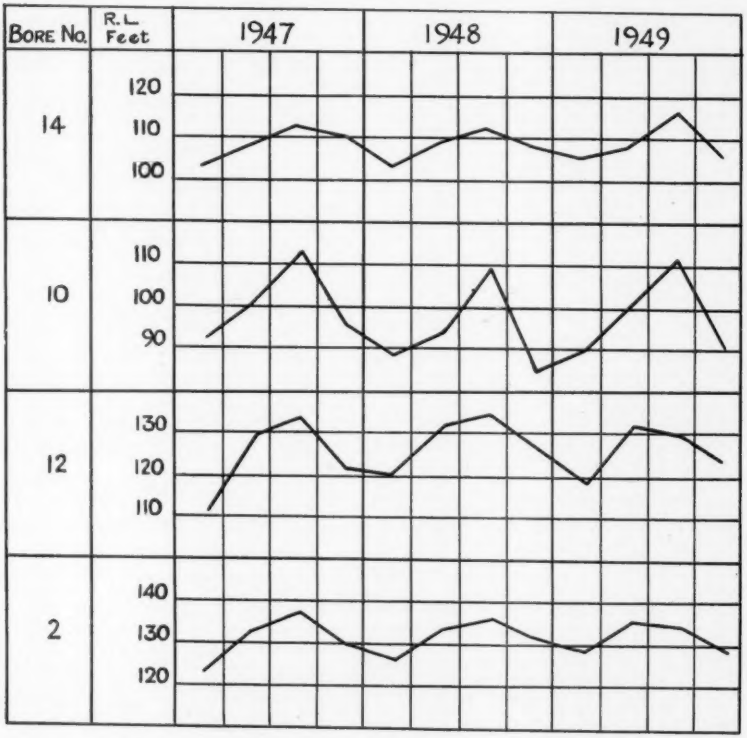


FIG. 6. Hydrographs showing seasonal fluctuation of subartesian water level in bores from the Adelaide Plains.

moved fairly rapidly through part of an aquifer the initial salts present in the beds have generally been flushed out and the water has lower salinity than in adjacent parts of the same beds where the ground water movement has been slower. Typical analyses of river water are given in Table 2.

Plotting of the general distribution of salinity in the underground water from various depths in the more closely settled areas west and southwest of the

TABLE 1.

SALINITY OF UNDERGROUND WATERS FROM AQUIFERS CUT AT DIFFERENT DEPTHS IN THE SAME BORE HOLE, ADELAIDE PLAINS.

Bore No.	Depth water cut (feet below surface)	Salinity (parts per million)	Aquifer
43	15	4,556	Recent sands
	90	29,275	Pleistocene sands
	272	5,023	Pleistocene gravel
	318	1,911	Pliocene sandstone
	345	1,615	Pliocene limestone
40	25	1,266	Recent gravel
	60	1,280	Pleistocene gravel
	135	1,223	Pleistocene sand
	219	1,850	Pleistocene gravel
	227	2,205	Pleistocene gravel
	400	699	Pliocene limestone
34	17	3,091	Recent sands
	140	776	Pleistocene sands
	220	379	Pleistocene sands
	386	751	Pliocene limestone
71	180	8,232	Pleistocene sands
	218	6,185	Pleistocene sands
	261	4,081	Pleistocene sands
	365	905	Pliocene limestone

city and in the Parafield-Salisbury districts, in the form of salinity contour diagrams, has revealed the presence of concentric zones of increasing salinity fanning out from the principal intake areas.

Principal areas of potable subartesian water (less than 1,450 parts per million), mainly from below 300 feet depth, are confined to two major well-de-

TABLE 2.

ANALYSES OF TORRENS RIVER WATER, ADELAIDE PLAINS.

Date	25/3/49	4/11/49
Ions and Radicles	Parts per million	Parts per million
Chlorine Cl	102.2	109.4
Sulfuric acid SO_4	nil	17.6
Carbonic acid CO_3	152	55.7
Sodium Na	63.1	72.5
Calcium Ca	43.9	16.3
Magnesium Mg	36.8	16.3
Total salinity	398.0	287.8
Hardness (English)		
Total	260.8	107.8
Temporary	253.8	93.1
Permanent	7.0	14.7
Due to calcium	109.6	40.7
Due to magnesium	151.2	67.1

TABLE 3.

ANALYSES OF ARTESIAN WATER, ADELAIDE PLAINS.

Bore No.	73	69
Date	21/10/48	21/10/48
Ions and Radicles	Parts per million	Parts per million
Chlorine Cl	242.4	365.4
Sulfuric acid SO_4	61.7	90.6
Carbonic acid CO_3	218.8	148.0
Sodium Na	210.2	231.3
Calcium Ca	50.0	53.2
Magnesium Mg	45.9	53.8
Fluorine F	1.0	0.7
Total salinity	829.0	942.3
Hardness (English)		
Total	313.8	354.1
Temporary	313.8	247.0
Permanent	nil	107.1
Due to calcium	124.9	132.8
Due to magnesium	188.9	221.3
pH value	7.6	8.1

fined regions—the Torrens-Sturt, and the Salisbury-Parafield areas covering approximately 46 square miles and 28 square miles respectively (Fig. 2).

Most of the water from these areas is suitable for domestic purposes or irrigation and for many industrial processes (Table 3). Principal objection is its hardness which ranges from 300 parts to 730 parts per million. Except in limited coastal areas most underground waters on the Plains are suitable for stock.

There is strong evidence of local contamination of the deeper subartesian water by very saline upper groundwaters, probably due either to casing failure in old bores, or to overpumping, in certain areas.

INTAKE AND DISCHARGE.

It has been calculated that the mean annual runoff from the hills to the plains is of the order 26,295 million gallons. Estimated mean annual intake into all ground water supplies from runoff and precipitation is approximately 23,750 million gallons over the whole area, and the recharge into the artesian basin is probably near 12,550 million gallons.

Estimated mean annual recharge into the Torrens-Sturt artesian area is 6,200 million gallons (4,600 m. gals. from the Torrens and tributaries, 1,600 m. gals. from the Sturt and Brownhill Creek); and into the Little Para artesian area 1,050 million gallons. These figures are tentative but are considered to be of the right approximate relative order.

Total annual discharge of underground water by pumping from all aquifers is probably a little over 2,700 million gallons at the present time. This is made up of about 1,150 million gallons from ground water and shallow aquifers and about 1,550 million gallons from artesian aquifers. Of the latter 1,000–1,200

million gallons comes from the Torrens-Sturt area and the remainder from the Little Para area.

A further potential draft at the rate of about 3,000 million gallons per annum, all from the Torrens-Sturt area, is available from the 50 odd Government owned wells held in readiness as an auxiliary service to Adelaide's metropolitan water supply.

It is apparent that the present rate of annual discharge is well within the safe yield capacity of the artesian basin, but also that a rapidly increased rate of pumpage could well accelerate the rate of lowering of the hydraulic surface within the areas of fresh water to such an extent that saline water from outside would migrate laterally towards the heavily pumped areas. This would cause saline water outside present areas of potable water to move in and result in a contraction of the area over which potable artesian water could be obtained.

There is obviously scope for much detailed study of the hydrological properties of the principal aquifers. Conditions are such that for the determination of permeability, and hence coefficients of transmissibility and storage, and safe yield of these aquifers, discharging well methods as outlined by Wenzel,[5] using either equilibrium or non-equilibrium formulas, will be most applicable. It is hoped to conduct field tests during the coming winter.

CONCLUSIONS.

The areas within the Adelaide Plains in which potable underground water suitable for either domestic use, irrigation or secondary industries can be obtained, are restricted within reasonably narrow limits both in extent and distribution.

This is particularly the case of the artesian or subartesian water, in which fresh water is confined to two major areas—the Torrens-Sturt flood plain area, and the Little Para flood plain area, which have been defined, and to an area within the flood plain of the Gawler River, which has not yet been completely delineated.

All areas of fresh artesian waters are closely related geographically to intake areas from surface water courses which drain excess rainfall runoff from the adjacent hills on to the Adelaide Plains. It is apparent that this meteoric water is the prime source of all underground water within the area investigated.

Outside of these restricted areas of potable or better quality water, subartesian water is available in lateral extensions of the same aquifers, but is too saline for domestic or garden use.

It is known that under present rates of pumping the hydraulic surface level is slowly declining, showing that some water is being removed from storage within the artesian aquifers.

While it is probable that many times the present rate of annual pumpage could be sustained for very many years and ultimately the decline in level would cease when the intake balanced discharge, the result of an accelerated large scale lowering of the level would be for water to migrate laterally towards

[5] Wenzel, L. K., Methods for determining permeability of water-bearing materials with special reference to discharging-well methods: U. S. Geol. Survey Water-Supply Paper 887, 1942.

the heavily pumped areas. This could cause a contraction in the areas over which potable water would be obtained.

It is evident, therefore, that further investigations of the artesian basins for the purpose of determining more closely the intakes, the trends of water level, salinity, and of estimating future drawdowns and safe yield, are most desirable. The peculiarly localized nature of the intake of fresh water into the artesian aquifers to the west and northwest of Adelaide points to the possibility of establishing centers of artificial recharge at these intake areas.

DEPARTMENT OF MINES,
ADELAIDE, SOUTH AUSTRALIA,
Oct. 17, 1950.

ENGINEERING GEOLOGY PRINCIPLES OF SUBTERRANEAN INSTALLATIONS.[1]

GEORGE A. KIERSCH.

CONTENTS.

	PAGE
Abstract	208
Introduction	209
Forces exerted by a subsurface explosion	209
Character of resisting medium	210
Site reconnaissance—design of installations	212
Inherent geologic structure	212
Depth of penetration (projectile)	213
Conditions of burden	213
Size and shape of openings	214
Utilizing existing openings	217
Geologic structure and the location of openings	217
Site exploration	217
Geologic interpretation	220
Drilling data	220
History of site rock	221
Depth of overburden-weathering and alteration	221
Physical characteristics of site rock	221
Forecasts—observations during construction	222

ABSTRACT.

Geologic factors that affect the location, construction, and operation of underground installations are primarily structural and petrographic. The energy from a subsurface blast is transmitted outward unequally in a heterogeneous rock. The degree of rock inhomogeneity is in direct ratio to the inability of the mass to resist near a blast the explosive pressure that is superimposed on the pre-existing inherent static stresses.

A pattern of rock failure resulting from explosive stresses has been empirically determined (McCutchen). The pressure front of a blast is considered to extend outward as an equal radial stress. Initial and most widespread failure is in tension and tangent to this front; shear planes develop within a smaller inner zone.

The size and cross-sectional shape of suitable openings are controlled by the cover: its depth, physical character, planes of inherent weakness, and possible active stresses. Existing openings may not be acceptable.

Reconnaissance surveys may be restricted both areally, due to operational factors, and by acceptable rock types. Geologically, site selection involves consideration of the degree of rock deformation, attitude of bedding-foliation, weathering and hydrothermal alteration, inherent active stresses, and water supply requirements.

[1] Part of this paper was presented before the Cordilleran Section, Geological Society of America, in Berkeley, California, April 16, 1949 as "Some Geologic Aspects of Underground Construction." Views expressed herein are personal and not necessarily those of any government organization or agency.

Sufficient geologic exploration and interpretation to determine the inherent structure, physical characteristics of rock, ground water conditions, a facies change, depth of weathering, and areas and zones of alteration must precede final plant design. This will involve regional studies and detailed surface and subsurface observations at the site. Core drilling, pilot bores, geophysics, and photo-geology may be used to advantage in specific locations.

The inherent structure may act either as a "protective barrier" or as an "avenue" transmitting destructive stress toward the opening, depending on its magnitude and location with respect thereto.

INTRODUCTION.

Considerations of national safety may dictate the subterranean location of factories and storage facilities. Current developments in destructive weapons are sufficiently advanced to shape a national policy. The purpose of underground installations may be either *tactical* where surface manufactured parts are stored and during an emergency assembled, or *operational*, where both the manufacturing and assemblage are so accomplished. Such re-location of vital plants will be highly selective, based on military importance, economic factors, and the solution of the geologic and engineering problems inherent in the construction and operation of such facilities.[2] Therefore only a small percentage of the production capacity of a nation could be protected in this manner.

The geologic principles and their application to the location, construction, and operation of subterranean installations designed to resist large scale subsurface explosions are discussed below. A relatively new field for the engineering geologist, it presents many problems common to mining and tunneling; any large scale subsurface building program would require the services of geologists with underground experience.

The writer's interest in these problems was initially stimulated during his connection with underground tests[3] carried on by the Corps of Engineers, U. S. Army. He has received many helpful suggestions from his former colleagues of the Sacramento District, Corps of Engineers, including R. C. Treasher. Stimulating discussions with Prof. C. W. Livingston, Colorado School of Mines, and Lt. Col. Wilmot R. McCutchen, Corps of Engineers, assisted the author. Thanks are due to Dr. Parry Reiche, Sacramento, and Dr. M. N. Short, Tucson, for critical review of the manuscript.

FORCES EXERTED BY A SUBSURFACE EXPLOSION.

A subsurface blast produces an unbalanced force, or explosive pressure,[4] on the rock mass in the vicinity. The tendency of this force to produce an acceleration of the rock can be realized only after both the mass inertia and the cohesion have been overcome.

[2] Robinson, C. F., Industrial vulnerability to bombing: Military Engineer, vol. 41, no. 279, p. 5, 1949.

[3] Gorman, Clyde J., Underground Explosion Test Program: Tech. Information Branch, Corps of Engineers, U. S. Army release, Sacramento, California, July 27, 1948.

[4] McCutchen, Wilmot R., The behavior of rocks and rock masses in relation to military geology: Colorado School of Mines Quart., vol. 44, no. 1, p. 64, 1949.

An explosion produces two general classes of elastic waves,[5] body waves and surface waves. The two body waves (compressional and shear) travel through the mass; the four surface waves (rayleigh, love, coupled, and hydrodynamic) travel along its surface. At practical depths of bomb penetration,[6] about 35 percent of the maximum potential compressional pressure will be exerted on the medium, the remaining 65 percent will be spent in producing an air blast and the cratering effects. If the surrounding medium is faulted, sheared, or closely jointed, part of the explosive pressure will be transmitted farther along these planes of weakness than would have been the case had no major structural breaks been present.

An empirical pattern of rock failure resulting from an explosion has been formulated from a study of craters. According to McCutchen,[7] the pressure front of a blast may be considered to extend outward as an equal radial stress in any homogeneous medium. Initial and most widespread failure is in tension, tangent to this pressure front. Shearing occurs within a smaller inner zone along planes inclined to the directions of maximum stress, as in conventional static strength tests.

An excellent discussion of the physical behavior of rock surrounding a tunnel opening which is subjected to a superimposed explosive stress has been given by McCutchen.[8]

CHARACTER OF RESISTING MEDIUM.

A homogeneous medium, capable of dissipating energy equally in all directions from a subsurface blast is probably non-existent in nature. Accurate evaluation of rock reaction to induced stress is complicated by its heterogeneity; structural weaknesses result in unequal transmission of stress in various directions (discussed below). Experience and judgment are requisite in estimating the degree of inhomogeneity which, in general, is a measure of the inability of the mass to resist stress nearby a blast. To this general rule the special cases of position such as shown in Figure 5 are exceptions. However, the importance of inhomogeneity as an "avenue" for transmitting stress from the blast area decreases with distance and position and its function as a "protective barrier" increases.

Igneous rocks often harbor residual stress due to volume changes during cooling after the magma froze. Igneous intrusions cause stresses in their host rocks. M. F. Boos[9] has reported that granite under a cover equivalent to 6,500 feet has been known to expand one percent on removal of burden. Consequently previously unrelieved stresses may cause rupture of fresh rock faces in excavations. Carl Terzaghi[10] has reviewed the possible state of residual stress in rocks and soils of various types.

[5] Leet, L. Don., Vibrations from blasting: The Explosives Engineer, p. 43, March–April 1946.
[6] Glasstone, Edward (editor), The effects of atomic weapons p. 112, U. S. Government Printing Office, Washington, D. C., 1950.
[7] McCutchen, Wilmot R., op. cit., p. 66.
[8] McCutchen, Wilmot R., op. cit., pp. 43–66.
[9] Boos, Margaret Fuller, Some geological conditions that favor rock bursts (abstract): Geol. Soc. America Bull., vol. 57, pp. 2, 1180, 1946.
[10] Terzaghi, Carl, *in* Proctor, R. V. and White, T. L., Rock tunneling with steel supports, The Commercial Shearing and Stamping Co., Youngstown, Ohio, pp. 47–85, 1946.

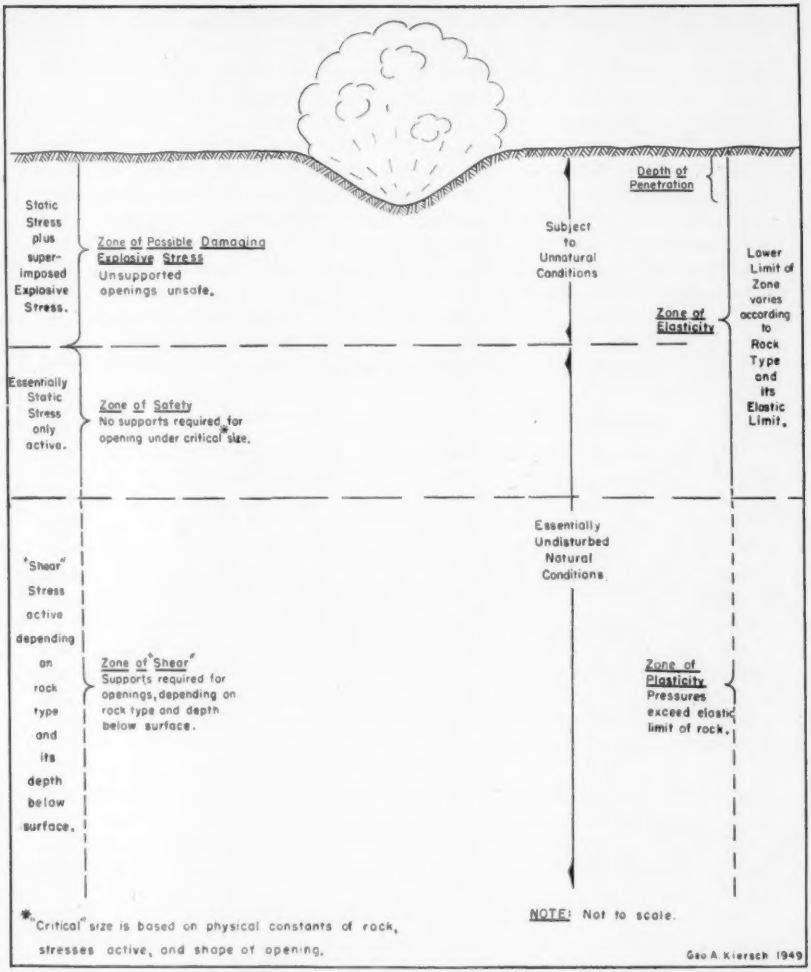

Depth of Penetration
Static Stress plus super-imposed Explosive Stress.
Zone of Possible Damaging Explosive Stress
Unsupported openings unsafe.
Subject to Unnatural Conditions
Zone of Elasticity
Lower Limit of Zone varies according to Rock Type and its Elastic Limit.
Essentially Static Stress only active.
Zone of Safety
No supports required for opening under critical* size.
Essentially Undisturbed Natural Conditions
"Shear" Stress active depending on rock type and its depth below surface.
Zone of "Shear"
Supports required for openings, depending on rock type and depth below surface.
Zone of Plasticity
Pressures exceed elastic limit of rock.
NOTE: Not to scale.
*"Critical" size is based on physical constants of rock, stresses active, and shape of opening.
Geo A. Kiersch 1949

FIG. 1. Generalized schematic diagram of the natural stresses present within a homogeneous rock mass at depth. The near-surface zone which is subject to unnatural explosive stresses is separated from the deeper seated zone of "shear" by an intermediate zone of safety. The boundaries and vertical extent of this safety zone will be controlled by the specific rock type and the degree of inhomogeneity of the rock mass.

The physical characteristics of an ideal rock mass and its reaction to a subsurface blast are indicated in Figure 1. The boundaries of the near-surface zone subject to a superimposed explosive stress varies locally, depending on the degree of rock inhomogeneity. Essentially undisturbed natural conditions will exist below its limits. At depth, the elastic limit of the rock is overcome by natural stresses. Therefore, any opening excavated below this depth will be located in the zone of plasticity; "shear" stresses are active and openings require supports. The depth to the zone of plasticity will vary with the specific rock type. The "shear" strength [11] of an average homogeneous sandstone is exceeded at a depth of 1,750 feet, while that of an average homogeneous plutonic rock is exceeded at 6,500 feet. The depth to the upper limit of the zone of plasticity will normally be less than the theoretical as the rock will be weakened by its inherent inhomogeneity.

The ideal location for underground openings is therefore confined to the zone of elasticity, below the limits of possible damaging explosive stress. Within this zone of safety, no supports would be required for openings under "critical" size.

SITE RECONNAISSANCE—DESIGN OF INSTALLATIONS.

The plan and cross-sectional size of underground openings must be known prior to site reconnaissance. Rock is assumed to offer the most advantageous protection; economical construction and maintenance presuppose a minimum or absence of support and reinforcement of openings. Unfavorable rock types and inherent structures can be overcome by supports and lining. However, subterranean installations will be costly enough, without the additional expense of reinforcement. The following discussion assumes that openings must stand unsupported or with only a minimum of short reinforced sections.

Inherent Geologic Structure.—Subterranean installations should avoid areas of closely spaced faults, fissures, shear zones, and folds. Other unfavorable features such as bedding plane faults, caverns, sheeting, pronounced foliation, zones of deep weathering and extensive hydrothermal alteration are restricted to certain rock types.

Joints may be so extensive and closely spaced that they assume major structural importance; normally however, spacing and tightness increase with depth. Abundant alteration products and clayey material associated with close-spaced joints or fractures cause "raveling," i.e., the rock tends to sluff and cave into an opening. Such joints facilitate ground water entry, which further increases "raveling" by its lubricating action.

Sites in moderately to steeply dipping bedded or foliated rock are unsuited to the design of some cross-sectional shapes, if this feature is a controlling factor. Such a site cross-cuts abundant inherent planes of weakness, either numerous unstable rock contacts or foliation; portal locations must guard against excessive lateral pressure requiring additional reinforcement. Excavation blasting will open hitherto tight breaks for a distance of several hundred feet and thereby facilitate the ground water drainage of a wide area the shape of an inverted cone.

[11] Schoemaker, Richard P., A review of rock pressure problems: A.I.M.E. Tech. Pub. 2495, p. 8, 1948.

Hyde Forbes [12] observed that a series of blasts for highway construction (600–2,500 pounds of powder each) detonated 40–60 feet above the roof of railroad tunnel No. 32 at Keddie, California, opened the foliation planes in the steeply dipping schist; consequently rock creep was facilitated and the concrete tunnel lining was buckled.

The marginal zones of fractured and altered rock, common to major structural breaks, may carry large quantities of water, in addition to the zone itself. Stratified rocks, especially where not essentially horizontal, should be carefully investigated for permeable, water-bearing members and contacts. An opening that cross-cuts an aquifer could develop a serious drainage problem.

Crustal deformation subjects a rock mass to new conditions and unrelieved stress may exist where accommodation is incomplete. The possibility of heavy active stresses must be evaluated; if present it will probably be uneconomical to attempt to reinforce for these additional stresses, and the site should be abandoned.

An inadequate water supply for plant operation may eliminate a site otherwise acceptable.

Depth of Penetration (Projectile).—The potential penetration depth of bombs and missiles will depend on several factors, among them the physical character of the resisting medium. Applied research will supply data for estimating the penetration depth of potential weapons in the commoner rock types. This data becomes a comparative guide for use in the plant design; the deeper the penetration, the greater will be that proportion of the potential explosive pressure which is exerted on the medium (less in cratering effects) up to a theoretical maximum of 100 percent,[13] located considerably below the practical limits of penetration.

Conditions Of Burden.—Suggested conditions of ideal cover for an underground installation are given in Figure 2. A competent rock of high-velocity charateristics at the surface, such as a rhyolite, basalt or limestone is considerably thicker than the potential depth of penetration for the center of the blast; it overlies an incompetent rock of low-velocity such as shale or weakly indurated sedimentary or volcanic material. Underlying these two contrasting rock types is the competent host rock for the underground openings.

The host rock should be a comparatively high-velocity medium, whether igneous, sedimentary, or metamorphic, which meets the previously established geologic specifications, i.e., physical properties and inherent structure. All underground openings are driven at a pre-determined depth below the surface based on the results of applied research and consistent with common tunneling and mining practice (Fig. 1).

Ideal burden conditions as outlined in Figure 2 result in two formational contacts between the surface rock and the openings. These boundaries are points at which only a partial transfer of the explosive pressure can be effected. Therefore each contact between rock types reduces the amount of explosive stress exerted on the underlying formation due to a reflection and dissipation of the explosive energy in the overlying medium. Consequently, the potential

[12] Forbes, Hyde, Written communication, November 1949.
[13] Glasstone, Edward (editor), op. cit., p. 112.

explosive pressure exerted on the rock type in which the openings are located is a small part of the total induced destructive blast.

A site that is blanketed by a thick cover of low-velocity soil overlying a competent host rock for the openings may not afford as much protection under normal conditions as the sequence suggested in Figure 2. The penetration depth of the blast center in such burden could be to the extent of penetrating the upper contact of the underlying high-velocity rock. Under these conditions

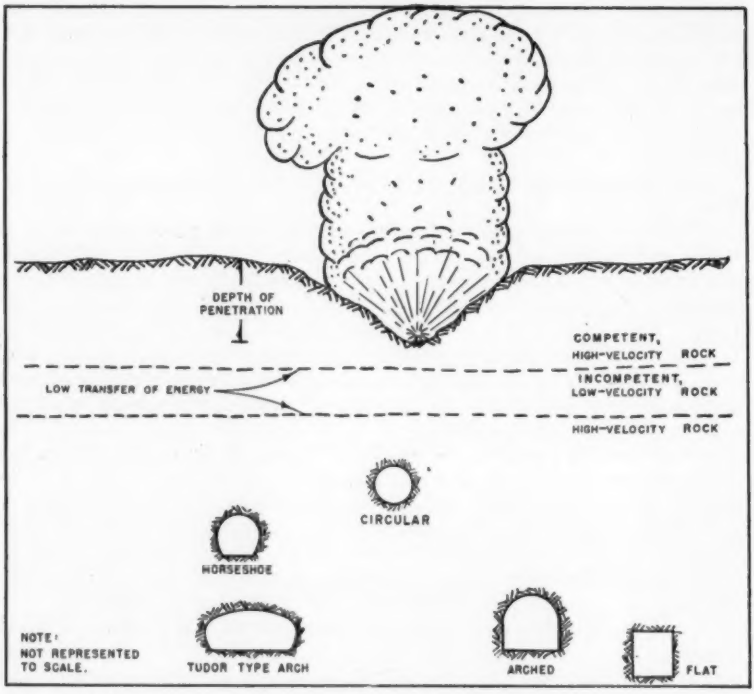


FIG. 2. Idealized sketch illustrating effective conditions of burden. Some of the common cross-sectional shapes of openings are shown.

of burden, a greater proportion of the induced explosive pressure would be exerted on the host rock mass.

Size and Shape of Openings.—Suitable openings [14] may incorporate certain features of the common tunneling shapes, namely the circular, horseshoe, arched, and flat-roofed or a combination of these as with the Tudor-type arch (Fig. 2) or those ideal shapes shown in Figures 3 and 4. Stress analysis

[14] Kiersch, George A., Underground space for American industry: Mining Engineering, vol. 1, no. 6, pp. 22–23, 1949.

studies by W. I. Duvall [15] have determined the relative ability of certain cross-sectional shapes to resist stress (Figs. 3, 4).

Rocks at depths probably approach hydrostatic stress conditions. Unloading by erosion may have partially relieved the vertical components of pressure. However, the horizontal stress components remain unrelieved. Therefore, in some rocks, depending on their geologic history, the horizontal stress may equal or be greater than the vertical stress. As rock masses at depth may

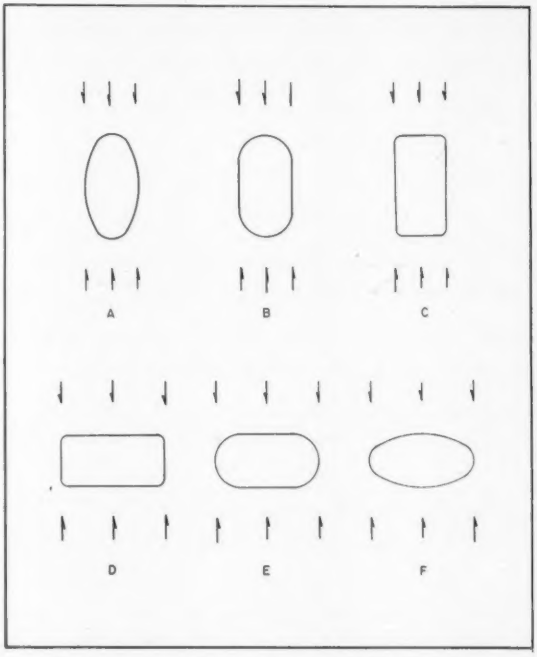


FIG. 3. Cross-sectional shapes of openings listed in their order of preference for use in a unidirectional stress field. (After Duvall, W. I., Stress analysis applied to underground mining problems, Part I: U. S. Bur. Mines Rept. Inv. 4192, Figure 15, 1948.)

thus be under varying combinations of horizontal and vertical stress, the cross-sectional shape of the opening excavated is of importance geologically, in addition to its design for operational space.

Within the near-surface zone subject to a superimposed explosive stress, (Fig. 1) forces can be exerted on an opening from other than a vertical direc-

[15] Duvall, W. I., Stress analysis applied to underground mining problems, Part I: U. S. Bur. Mines Rept. Inv. 4192, pp. 12–13, 1948.

tion. Therefore an opening located herein must be designed to resist varied directional explosive stress.

Small bores of 6 to 10 feet in maximum dimension will stand unsupported in numerous rock types and under unfavorable geologic conditions. However, as underground installations will certainly require at least part of their openings to be several times these dimensions, the character of the site rock increases in importance. Large sized openings will stand unsupported in a much smaller number of rock types.

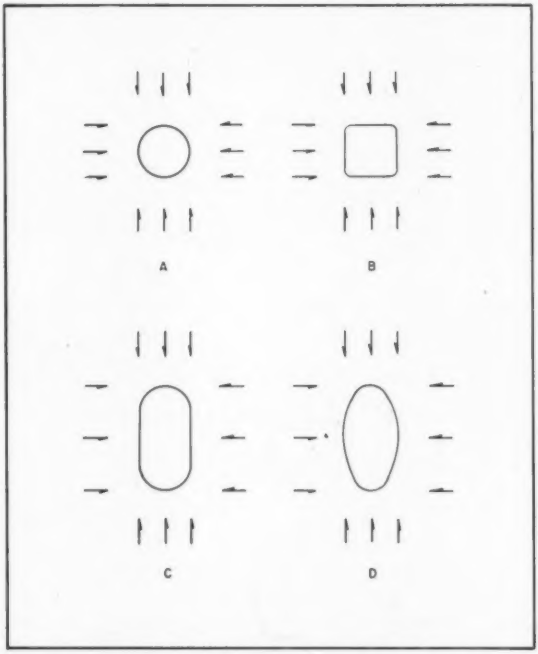


FIG. 4. Cross-sectional shapes of openings listed in their order of preference for use under a hydrostatic stress field. The common tunneling shapes shown in Figure 2 would fall between "A" and "B" in preference, the Tudor-type arch after "D." (After Duvall, W. I., Stress analysis applied to underground mining problems, Part I: U. S. Bur. Mines Rept. Inv. 4192, Figure 16, 1948.)

Subterranean installations will undoubtedly require the construction of large multiple openings connected by smaller passageways. Consequently the design must consider the spacing between the parallel openings for an adequate distribution of the stress in the pillars (discussed by Duvall [16]).

[16] Duvall, W. I., Stress analysis applied to underground mining problems, Part II: U. S. Bur. Mines Rept. Inv. 4387, 1948.

Their size and shape may require a compromise between the space requirements and the physical limits of the site rock.

Utilizing Existing Openings.—Undoubtedly many existing caves and abandoned mines are ideal or could be modified for subterranean installations. However a large number of the existing openings would require such extensive modification to meet specifications that their use would be uneconomical. In addition to the various military and operational aspects controlling their use, existing openings may be unfit for modification due to such geologic features as a host rock with abundant inherent planes of weakness, extensive alteration of host rock, inherently weak cross-sectional shapes, excessive ground water, cross-sectional size inadequate to meet specifications, and openings located too shallow or too deep below the surface (Fig. 1).

New excavations completed by highly mechanized methods will probably compare favorably in cost and required completion time to an expensive modification of existing openings. For example, a 25 foot horseshoe shaped tunnel was driven in granitic rock at the rate of 206 feet per week [17] (three shift basis) on a hydro-electric project in California recently.

Geologic Structure and the Location of Openings.—A rock mass may vary widely in its resistance to explosive pressures depending on: the physical character of the mass, the magnitude and abundance of the inherent planes of weakness and their position with respect to the blast.

The effect of the geologic structure on the propagation of energy from a subsurface blast and its expected induced stress exerted on underground openings is illustrated in Figure 5. Opening number 1 would be safer than opening number 2 as the shear or fault zone will act as an "energy barrier" by its dissipation and reflection of the explosive pressure. Only a small percentage of the explosive stress will be transferred across this weak section and exerted on the rock mass near opening number 1. A larger proportion of the explosive stress would be exerted on opening number 2, facilitated by the preexisting weaknesses (joints). Enough energy could probably be transferred to cause damage herein.

Opening number 3 would be more dangerous than either openings number 1 or 2. The shear or fault zones would act as "energy barriers," thereby confining a large percentage of the induced explosive stress within this structural block. Consequently, the explosive pressure active herein would be capable of exerting a stress of damaging proportions deeper.

Likewise, if the blast occurred to the right or left in Figure 5 the comparative safety of the openings illustrated would shift.

Whenever possible, alignment of underground openings normal to the strike of any major planes of weakness will minimize the use of reinforcing supports.

SITE EXPLORATION.

The results of a regional geologic reconnaissance survey followed by detailed areal mapping should be available for use in planning the site exploration

[17] Pacific Gas and Electric Progress, p. 4, January 1949.

program. A photo-geology survey may be helpful to detect structurally weak areas in the field; questionable structures should be further evaluated on the ground as possible localities for detailed exploration.

A core-drilling program which may include vertical, inclined, and horizontal holes may be necessary to evaluate adequately a site prior to the final selection. Major zones of weakness and questionable areas which are concealed should be investigated. The NX size diamond drill bit (2⅛ inch core) will normally

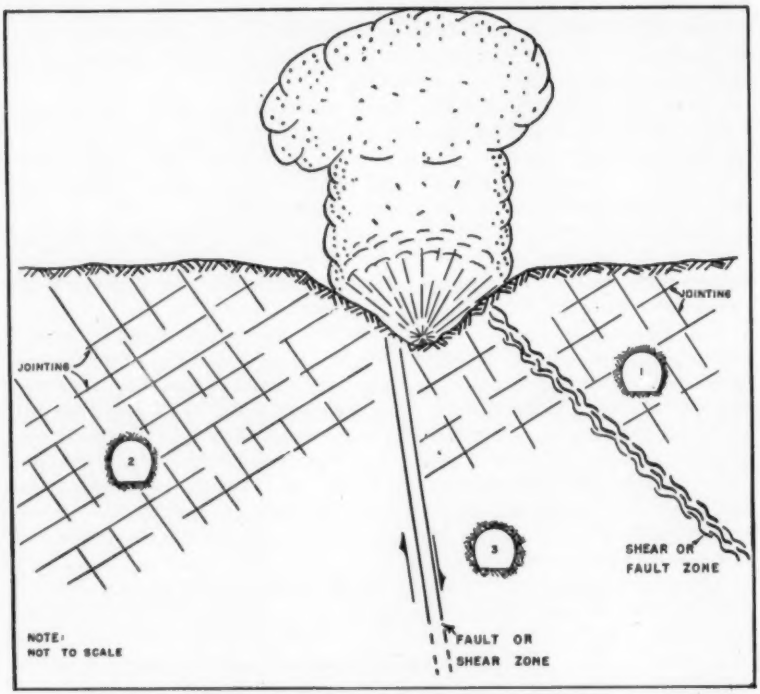


FIG. 5. Idealized sketch illustrating geologic planes of weakness with respect to underground openings. The relative importance and effect of the inherent structure will depend on its magnitude and position with respect to the blast and subsurface opening.

give higher core recoveries with subsequently more geologic information than smaller sized holes. In certain cases, a pilot bore may be driven as a phase of the exploration program and utilized later in the construction cycle and plant operation (discussed elsewhere [18]).

[18] Kiersch, George A., op. cit., pp. 23–24.

Certain types of geologic information can be obtained by geophysical methods of exploration at less cost and more quickly than by drilling or other means. Subsurface structural conditions, water-bearing horizons, depths of overburden, or the thickness of a stratigraphic sequence can be accurately outlined. Best results are assured when several widely spaced cored drill holes are available as an aid to interpretation and correlation of the geophysical data. Generalized sketches of the engineering geologic problem, the geophysical method applicable, and the type of data collected are given in Figures 6 and 7.

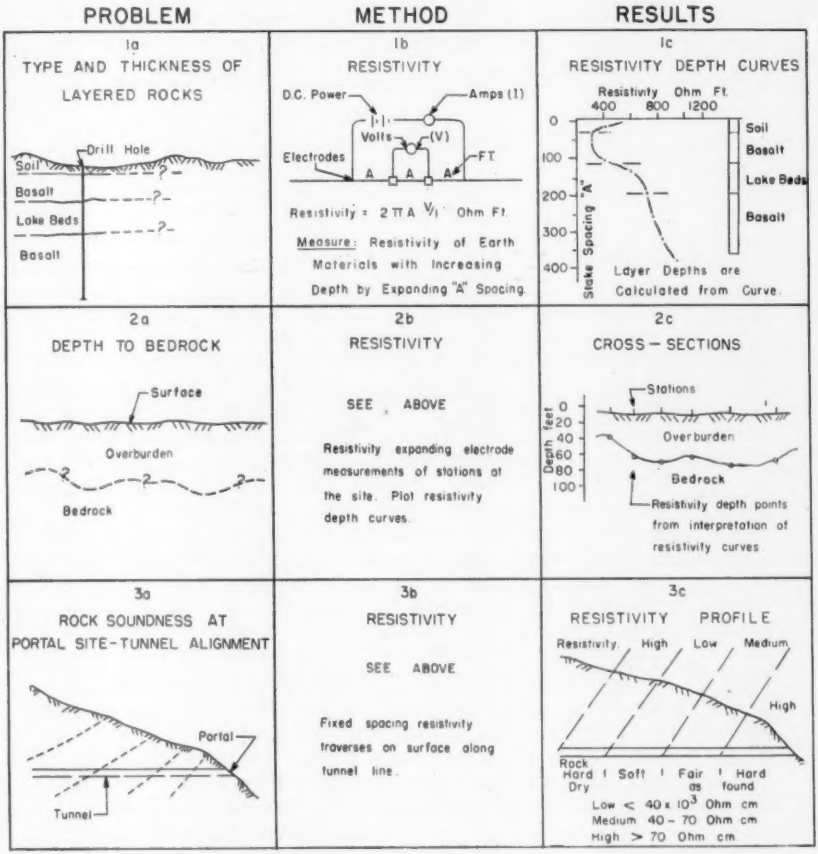


FIG. 6. Resistivity geophysical methods applicable to geologic problems common in subterranean construction. Modified with permission after a series of drawings by Dart Wantland in the chapter by George Robb of "Subsurface geologic methods," Colorado School of Mines Quart., vol. 44, no. 3, pp. 807–08, 1949.

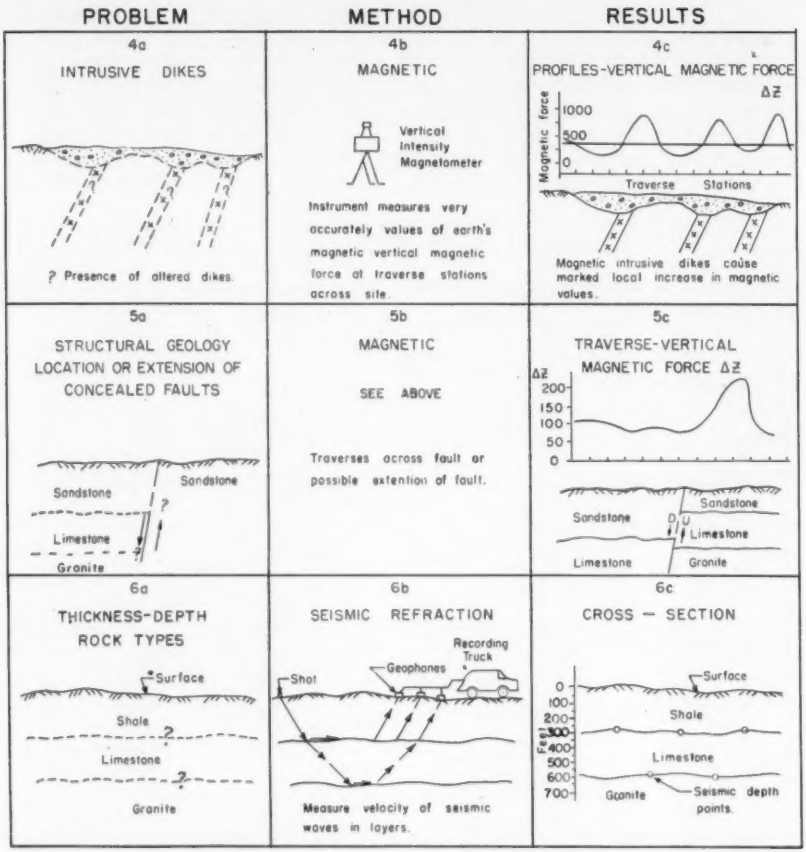


FIG. 7. Magnetic and seismic geophysical methods applicable to geologic problems common in subterranean construction. Modified with permission after a series of drawings by Dart Wantland in the chapter by George Robb of "Subsurface geologic methods," Colorado School of Mines Quart., vol. 44, no. 3, pp. 809–810, 1949.

A thorough exploration program at any site may prove an unfavorable geologic condition of controlling importance.

GEOLOGIC INTERPRETATION.

Drilling Data.—A study and correlation of the drill core information with the surface geology will further outline the structural and petrographic conditions at any site. Structural features can be projected on cross-sections to the level of the proposed installation as a forecast for use in the design and con-

struction phases. Detailed examination of the drill core by experienced personnel may reveal evidence of any of the unfavorable geologic conditions discussed above.

History of Site Rock.—The regional geologic history will undoubtedly aid in estimating the general structural conditions present at any potential site. For example, a Precambrian granitic mass which has undergone several periods of deformation and is extensively jointed and sheeted may not compare structurally to a site in similar rock of younger age. Likewise an older limestone formation which has been subjected to a humid climate during its geologic history may be more cavernous and permeable to circulating ground water than a limestone of younger age. In contrast, an older, more highly metamorphosed rock may be superior for underground construction to a younger, less metamorphosed formation, because the inherent structural weaknesses have been fused and healed by repeated cycles of deformation.

The possibility of unrelieved rock stress is more likely in an area which has undergone relatively recent geologic activity.

Depth of Overburden-Weathering and Alteration.—Subsurface exploration combined with an interpretation of the surface geologic conditions both regional and areal should outline the expected depth of overburden and weathering.

Extensive areas or zones which have undergone hydrothermal alteration present similar problems. Large sections of a site may be altered at depth, although surface evidence is lacking. Subterranean installations should avoid areas of intense hydrothermal alteration, as hydration and chemical action follow exposure of the altered rock, causing the material to swell and slump into the opening and thus necessitate supports.

Sizeable faults and shear zones with their commonly associated margins of altered country rock will present similar problems. The contacts of hydrothermally altered dike rocks are normally unstable; in addition, their plastic "running" character will require support.

Physical Characteristics of Site Rock.—The tensile and shear strengths of representative specimens of the site rock can be determined by standardized tests as outlined by Obert and others.[19] Combination of all data on the physical constant characteristics of a proposed site rock will permit rough comparison of its suitability with that of rock masses previously tested and studied. The inhomogeneity of all site rocks, however, makes precise comparisons impossible.

In order to supplement field and physical constant data of a proposed site rock, experimentation with small-scale laboratory models reproduced in accordance with the principles of similitude have proven to be valuable.[20] Recent studies [21] in the mining research laboratories of the Colorado School of Mines utilize an impact testing device and a brittle lacquer Stress-coat on photoelastic material to study transmission of the explosive stress induced by a subsurface blast in a medium.

[19] Obert, Leonard, Windes, S. L., and Duvall, Wilbur I., Standardized tests for determining the physical properties of mine rocks: U. S. Bur. Mines Rept. Inv. 3891, 1946.

[20] McCutchen, Wilmot R., op. cit., pp. 66–72.

[21] Livingston, Clifton W., Mining engineering at the Colorado School of Mines: Mines Mag., vol. 40, no. 3, pp. 42–43, 1950.

Studies of blast craters (discussed above) have concluded that initial and most widespread failure of a rock mass is in tension. Likewise initial failure by rock bursts and popping at the back and floor of underground openings has been shown to be caused by rupture in tension. Consequently, the tensile strength of the site rock affects or controls its resistance to any explosive stress acting on an opening, in addition to influencing the maximum size, shape, and the tunneling method employed. A discussion of several possible tunneling methods and their cross-sectional shapes has been given elsewhere.[22]

FORECASTS—OBSERVATIONS DURING CONSTRUCTION.

All geological features, both unfavorable and advantageous, which will affect any phase of the design, construction cycle or maintenance of an underground installation justifies consideration. Initial interpretation of the subsurface conditions based on a correlation of the exploration data and surface exposures may require modification as excavation progresses. An up to date interpretation, based on a correlation of surface and subsurface exposures and the exploration data can anticipate conditions beyond the working face; areas most likely to be damaged by underground blasts should be avoided.

A detailed geologic map of all openings comprising the installation should be completed as soon as practical after excavation. A suggested method is to map each rib section of the opening separately as projected onto a vertical plane (profile) and the roof section as projected onto a horizontal plane. A detailed correlation of all structural and petrographic features between the ribs and roof is then readily accomplished by inspection, when the strip maps are placed in their position side by side. This map will serve as a lasting record for review and consultation in case of damage to any part of the subterranean installation; its uses and value for those sections that are supported or lined are inestimable.

The engineering geologist can assist in estimating the requirements for reinforcing supports if squeezing or caving ground is encountered. Gages[23] for measuring the static (residual) stress in the walls of a tunnel have been developed and successfully used by the U. S. Bureau of Reclamation for determining reinforcement needs.

U. S. DEPARTMENT OF STATE,
INTERNATIONAL BOUNDARY AND WATER COMMISSION,
ALPINE, TEXAS,
Oct. 5, 1950.

[22] Kiersch, George A., op. cit., pp. 22–25.

[23] Rhoades, Rodger, Geological and related activities in the Bureau of Reclamation, July 1948–1949 (abstract): Geol. Soc. America Bull., vol. 60, no. 12, p. 1916, 1949.

AN OCCURRENCE OF NATIVE GOLD IN AN ICE LENS—GIANT-YELLOWKNIFE GOLD MINES, YELLOWKNIFE, NORTHWEST TERRITORIES.[1]

R. W. BOYLE.

ABSTRACT.

An unusual occurrence of native gold enclosed in ice is described. Two types of gold were observed—foil gold and sponge gold. The foil gold occurred within the ice, and the sponge gold was found as incrustations on calcite and pyrite crystals. The gold is thought to have been deposited from migrating solutions which may have leached an adjoining ore shoot of some of its gold values.

INTRODUCTION.

RECENTLY, a phenomenal occurrence of native gold enclosed in ice was found by A. McCutcheon, a mining engineer, at the Giant Mine, Yellowknife, Northwest Territories. This occurrence was brought to the attention of the author who examined it and obtained specimens for study. This paper is intended as an outline of the observed facts, but the conclusions that follow should be considered only tentative until more thorough examinations and analyses are completed.

The Giant Mine is one of the foremost gold producing mines of the Yellowknife region. The ore bodies of this mine occur within shear zones in Archean greenstones that have been much folded and faulted. Two distinct periods of faulting have been recognized within the region. The first period is marked by shear zones that enclose the gold ore bodies of the producing mines. The age of this faulting is generally considered to be Archean. The second period of faulting is marked by many fractures and transcurrent faults that are characterized by fault breccia and gouge partially replaced and cemented locally by quartz and carbonate minerals. The West Bay fault and other major transcurrent faults are typical examples. These are generally considered to be of Proterozoic age. For descriptions and relationships of these faults and fractures the reader is referred to published accounts by Campbell,[2] Jolliffe,[3] and Henderson.[4]

The ore bodies of the producing mines consist of quartz veins and quartz replacement bodies within the early Archean shear zones. The ores contain pyrite, arsenopyrite, sphalerite, stibnite, bornite, chalcopyrite, gold, and sev-

[1] Published by permission of the Director-General of Scientific Services, Department of Mines and Technical Surveys.

[2] Campbell, N., West Bay Fault, *in* Structural Geology of Canadian Ore Deposits, a Symposium, Can. Inst. Min. Metallurgy, pp. 244–259, Montreal, 1947.

[3] Jolliffe, A. W., Yellowknife Bay-Prosperous Lake Area, Northwest Territories: Canada, Geol. Survey, Paper 38–21, 1938.

[4] Henderson, J. F., and Brown, I. C., Preliminary Map, Yellowknife, Northwest Territories: Canada Geol. Survey, Paper 48–17, 1948.

eral sulpho-salts, chief of which are tetrahedrite and jamesonite. Some of the gold in the ores occurs as small particles in minute fractures in the quartz, schist, and sulphides. The remainder of the gold is intimately associated with the numerous sulphides, and roasting methods are necessary for extraction.

The major ore-bearing shear zones of the region are cut and offset by many of the faults and fractures of Proterozoic age. In many localities the late faults and fractures contain a characteristic group of minerals of which the most abundant are quartz, carbonate minerals, hematite, galena, and chalcopyrite. The galena and chalcopyrite occur with comb quartz and carbonate minerals. The hematite is found in seams in the wall rock adjacent to the faults and fractures and is especially abundant in the large quartz stockworks which are an outstanding feature of the Proterozoic faults. None of the late faults and fractures have produced a gold ore body, and with the exception of the fracture described below, samples of the vein material when assayed indicate nil or trace amounts of gold.

DESCRIPTION OF THE OCCURRENCE OF THE GOLD IN THE ICE LENS.

The near surface extensions of the Proterozoic faults and fractures lie within the permafrost zone and contain ice lenses that are probably due to the freezing of ground water in the faults and fractures during Pleistocene time. Bateman [5] has discussed the depth and significance of the permafrost zone at the Giant Mine in a recent paper.

The gold occurs in an ice lens in a relatively flat fracture that offsets an ore shoot in a quartz replacement body in the 208 stope (No. 2 shaft) of the Giant Mine. This fracture occurs at a depth of 75 feet and is within the permafrost zone. The fracture varies from 2 to 6 inches in width and contains a mass of fault gouge and unoriented fragments of quartz and schist that have been cemented by small lenses of crystal clear ice.

The mineralization of the fracture containing the gold is characteristic of many others that have come under the author's observation with the exception that gold occurs in this particular case. Calcite is abundant, is pink to white in color, and occurs in vugs within the gouge and as incrustations and comb structure on the fracture walls. Cockade structures, consisting of crusts of small calcite crystals surrounding small fragments of quartz and schist, occur suspended within portions of the ice lenses. The crystals of calcite are either rhombohedrons or scalenohedrons, but many crystals show various modifications. Fine earthy varieties of carbonate minerals seam the gouge, and stalactic-like masses of discolored carbonate were noted clinging to portions of the fracture walls. Fine specks of hematite occur within and in close proximity to this particular fracture. This mineral appears in part to encrust the calcite and in part to form a reddish mixture with the earthy carbonate. In a few places a general impregnation of the quartz and schist of the ore shoot by hematite has occurred. Small cubic crystals of pyrite are sparingly distributed in some of the calcite vugs and comb structure and in the com-

[5] Bateman, J. D., Permafrost at Giant Yellowknife: Royal Soc. Canada Trans., vol. 43, ser. III, Section 4, pp. 7–11, June 1949.

minuted quartz and schist of the gouge. Orpiment occurs as earthy yellow coatings on portions of the gouge.

The ice lens that contained the gold occupied a medial position between the calcite encrusted walls of the fracture. It averaged 3 inches in width and was approximately 3 feet in length. Its nature could be described as an elongated vug filling. Other small ice lenses occupied similar central portions of the fracture. The major portion of the ice lens containing the gold was relatively pure, but portions cemented an unoriented mass of quartz and schist fragments, gouge, and cockade calcite structures.

The gold occurred in appreciable amounts as tissue paper thin splendent foil and as small golden brown spongy masses. The two types occur in close relationship with each other but under different conditions.

The main occurrence of splendent foil gold was found within the clear portion of the ice lens and was several square inches in area. The foil gold occurred in irregular connecting films, which were so delicate in structure that they collapsed under their own weight when the ice containing them melted. Detailed observations of the gold films indicated that they possessed a general vertical orientation and were all intricately connected in a ramifying network. Other small films projected out into the ice from the cockade calcite structures.

The small masses of sponge gold were restricted to the irregular incrustations and vugs of calcite that lined the fracture. The masses were found clinging to the crystals of calcite, lining open spaces within the vugs and comb structure of calcite, and incrusting small cubes of pyrite within the calcite vugs. In one small vug thin films of the splendent type of gold were associated with the sponge type, and high power magnification indicated that the two types may be gradational in structure. Sponge gold was not observed in the ice and melted samples failed to reveal its presence.

DISCUSSION.

The occurrence of native gold in ice is a phenomenon not easily explained. To the author there seem to be four possible mechanisms by which the gold could have been concentrated within the late fracture and the ice lens. These can be summarized as follows: (1) The gold was washed into the fracture from the surface and was cemented in place by the ice lens. (2) The gold was deposited on the fracture walls and was later spalled off by the crystallizing ice. (3) The gold was deposited from the water during the freezing and formation of the ice lens. (4) The gold was leached from the adjoining ore shoot by migrating solutions and was deposited along the fracture walls and in fractures within the ice lens. Each of these mechanisms can now be examined in the light of the facts presented.

The first of these mechanisms does not seem to answer any of the facts presented. The depth consideration, the nature of the sponge gold, and the interconnected nature of the foil gold seem to contradict a mechanism of mechanical concentration of the gold.

If spalling of the gold from the fracture walls had taken place during the crystallization of the ice lens one would expect to find sponge gold but ob-

servations indicate otherwise. Some sponge gold does occur on calcite crystals forming the cockade structures within the ice, but these structures appear to have formed after consolidation of the ice lens, and even granting the possibility that they were spalled from the fracture walls, it is difficult to see how this could have taken place without breaking loose some of the delicate masses of sponge gold. Furthermore, it is difficult to conceive how spalling of film gold from the fracture walls could have produced the interconnected network of splendent foil gold. The second mechanism apparently does not offer a possible explanation for the phenomenon.

The third mechanism is deposition of gold from circulating waters within the fracture during the formation of the ice lens. It is a known fact that several Proterozoic faults and fractures are water courses below the permafrost level. The author has examined several of these and has found that carbonate minerals and iron sulphides are at present either being deposited by, or at least are stable in, the flowing waters. Some of the waters issuing from the faults into the underground levels of the mines are charged with hydrogen sulphide and contain traces of arsenic. The origin of these waters is not known. They may be ground waters or very late juvenile waters. The carbonate, iron, and arsenic are presumably due to leaching of the ore zones by the circulating waters, but the origin of the hydrogen sulphide has not been definitely established. During Pleistocene time the waters may have carried small amounts of gold in solution and may have deposited it on the calcite encrusted walls as sponge gold. The origin of the gold was probably due to leaching of the adjoining ore shoots, but there is a possibility that it may have been very low temperature hydrothermal. This mechanism can account for the sponge gold but seems to fail when the foil gold is considered unless one resorts to some process whereby the foil gold was deposited in the ice lens during its solidification. This process may have taken place and the third mechanism may offer a possible answer to the problem.

The fourth mechanism seems to the author to be the most likely. This requires first the solidification of the ice lens in the fracture, and a later leaching of the gold from the adjoining ore shoot by migrating solutions with subsequent deposition along the fracture in the form of sponge gold and in the ice lens as splendent foil gold. The vertical orientation and interconnection of the foil gold certainly suggest deposition and growth of the gold in crystalline form within fractures in the ice, and it is difficult to envisage any other mechanism by which these features were produced. The sponge gold is restricted to incrustations on calcite and pyrite, and it may well have been that these two minerals exerted a peculiar depositional effect on the solutions carrying gold causing them to deposit sponge gold whereas deposition within the ice proceeded with the formation of foil gold. This view would seem to be the best in attempting to answer the problem of the occurrence of the sponge gold on the calcite crystals in the cockade structures in the ice.

CONCLUSIONS.

Of the four mechanisms given the latter two appear to offer possible explanations for the phenomenon. The author favors the last mechanism be-

cause it seems to answer the majority of the facts of the occurrence. Whatever the mechanism, it appears certain that the gold was deposited very late in geological time, possibly post-Pleistocene.

More work is being done to determine the exact nature and origin of the gold. Analyses of the water from the melted ice which contained the gold are in progress. Studies of the circulating waters from other fractures are being undertaken to determine if gold is moving in these waters. It is hoped that other occurrences may be found, and that specimens of the ice can be preserved for study in a refrigerated laboratory.

The author will welcome discussion of the proposed mechanisms of concentration, or others which may be suggested.

ACKNOWLEDGMENTS.

The author wishes to thank Dr. J. D. Bateman, geologist at the Giant Mine, and Dr. R. E. Folinsbee, Professor of Geology at the University of Alberta, for reading this paper and offering their criticism. Both of these men have observed the occurrence described.

Drs. G. B. Langford, E. W. Nuffield, and F. G. Smith have very kindly criticized this paper and have discussed with the author the various mechanisms suggested for the concentration of the gold.

DEPARTMENT OF GEOLOGICAL SCIENCES,
UNIVERSITY OF TORONTO,
Feb. 1, 1951.

SCIENTIFIC COMMUNICATIONS

CRYSTAL GROWTH AND DIRECTION OF SOLUTION FLOW.

There has been considerable interest in the asymmetric growth of crystals caused by directional feeding. The work of Newhouse [1] is an excellent example of an ingenious approach to the analysis of the direction of flow of mineralizing solutions from the asymmetry of crystals.

In the course of some experimentation in our laboratory, we took pictures showing successive stages of growth of seed crystals of potassium nitrate (orthorhombic). Crystals were grown in a simple apparatus, in which flow of solutions was controlled by convection.[2] The seed crystals were mounted

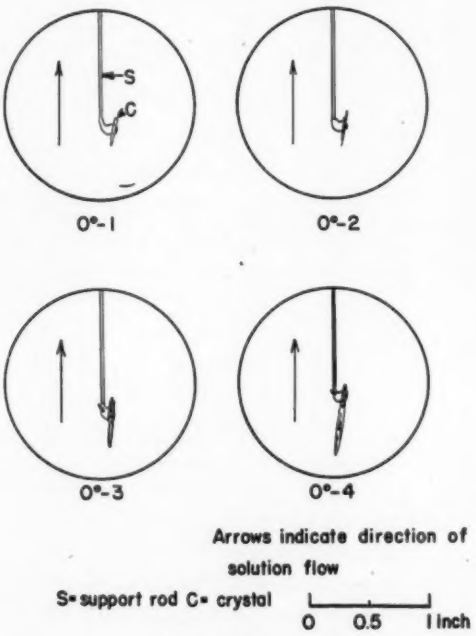


FIG. 1. Run 1.

[1] Newhouse, W. H., The direction of flow of mineralizing solutions: ECON. GEOL., vol. 36, no. 6, pp. 612–629, 1941.

[2] Jones, C. L., Garrels, R. M., and Howland, A. L., Apparatus for studying crystal formation: Science, vol. 105, no. 2715, p. 46, 1947.

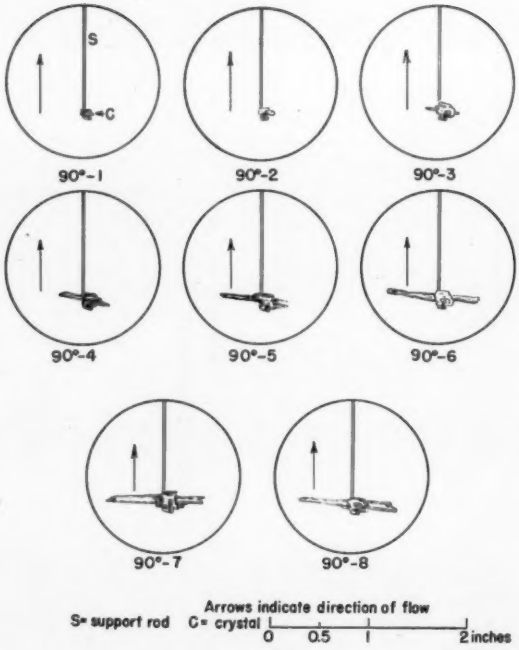


FIG. 2. Run 2.

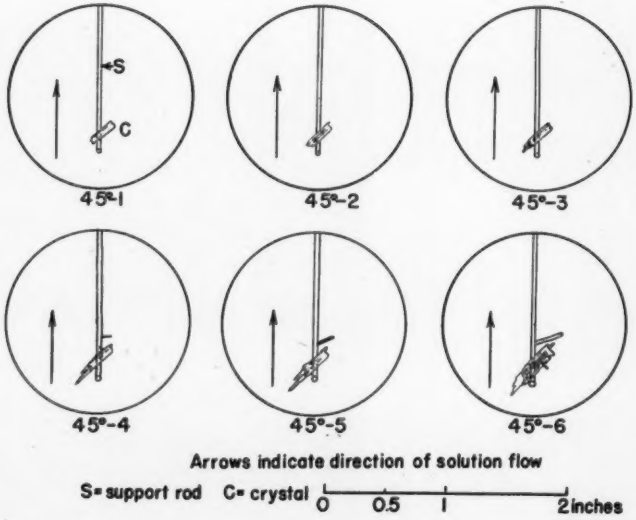


FIG. 3. Run 3.

in different positions in each of the three runs. In the first, the C axis of the crystal was mounted parallel to the direction of flow of the supersaturated solution; in the second run, it was oriented at right angles to the flow; and in the third case, at 45° to the flow. The changes occurring during growth are shown in Figures 1 to 4.

It is clear that in this particular case, the major control of the addition of new material was the crystallographic orientation rather than the direction from which the supersaturated solution came. Careful scrutiny of the photograph (Fig. 4) shows that, although the major asymmetry is attributable to

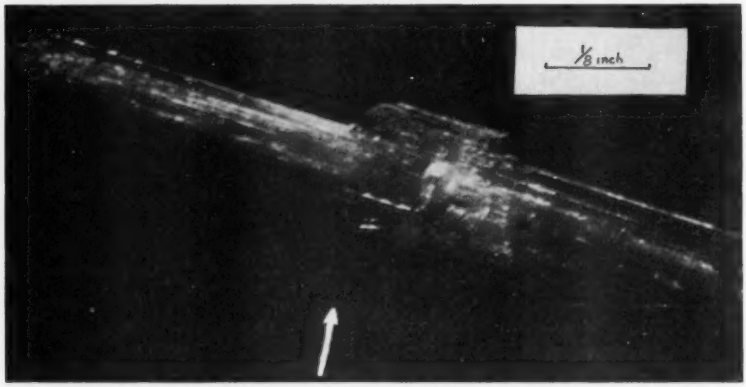


FIG. 4. Crystal of potassium nitrate grown from solution flowing in the direction indicated by the arrow. The seed crystal originally was mounted on top of the spherical mass of glue in the center of the crystal. Crystal is elongated parallel to the C-axis. The photograph corresponds to drawing 7 in Figure 2.

the crystallographic orientation, there also is asymmetry resulting from the direction of feeding. The spherical mass in the center of the crystal is a drop of glue on which the original seed was mounted. From this, it appears that the crystal has thickened downward (in the direction of feeding) much more than on the lee side. Also, intensive study of the left end of the crystal shows that the crystal has lengthened more on the "fed" side than on the lee.

Newhouse, of course, discussed the effect of crystallographic orientation, and stressed the advantages of using isometric crystals. The example cited simply emphasizes the fact that crystallographic orientation may cause growth effects that almost entirely obscure asymmetry resulting from direction of addition of material.

ROBERT M. GARRELS.

DEPARTMENT OF GEOLOGY,
NORTHWESTERN UNIVERSITY,
EVANSTON, ILL.,
Dec. 16, 1950.

DISCUSSIONS

THE EMERALD ISLE COPPER DEPOSIT.

Sir: The following is in reply to the discussion of my paper on this deposit by Mr. Fred Searls, Jr. (ECON. GEOL., vol. 45, No. 2). Mr. Searls conducted investigations at the Emerald Isle deposit a year after I had finished my field work in the area, and he has obtained welcome additional information. In particular, the seismic evidence which he reports, indicative of a series of faults along the east margin of the Sacramento Valley, is extremely valuable in substantiating the block-fault nature of the structure in this portion of the Basin and Range Province.

The chief purpose of Searls' discussion, however, is to support a supergene source for the mineralizing solutions at the Emerald Isle deposit, as opposed to the hypogene source which I favor (ECON. GEOL., vol. 44, No. 8). Such division of opinion has long existed among the geologists and engineers who have examined the deposit. The problem was summarized by an anonymous author [1] twenty-one years ago:

> Two theories have been presented many times as to the genesis of this ore. One is that it is secondary and is a re-deposition of solutions from the copper deposits in Mineral Park country at a much higher altitude than the Emerald Isle ground, which have gravitated to the place of the present deposition. Just what chemical reason can be presented for the deposition at this particular place remains unstated. The other theory is that there is a vein through which the copper solutions ascended from the depths below and which have percolated out into the country rock forming the rather extensive horizontal measurements of the ore bodies. The second theory appears quite acceptable at the present time.

The second theory still seems preferable to me, and I hope that the following analysis will strengthen its acceptability to others.

Disseminated Sulfide Deposit as a Source for Supergene Solutions.—Mr. Searls and Mr. Arthur Storke, by geophysical means, found that the Mineral Park "porphyry copper" deposit extends beneath the alluvium cover west of the face of the Cerbat Range and is adjacent to the chrysocolla deposit of the Emerald Isle. This is strong confirmatory evidence for a source of supergene solutions and is emphasized by Mr. Searls as overcoming the difficulty of having a topographic high between the Emerald Isle deposit and Mineral Park Wash, which drains the main portion of the sulfide mass. That such solutions could exist was stated in my previous paper [2] and is not in dispute, for a northward extension of the same disseminated sulfide mass occupies the headwater basin that supplies intermittent flow along the bedrock of the Emerald Isle country.

[1] Mohave County Miner, Boulder Dam edition, Kingman, Arizona, 1929.

[2] Thomas, Blakemore E., Ore deposits of the Wallapai District, Arizona: ECON. GEOL., vol. 44, No. 8, pp. 663–705, 1949.

The presence of this "porphyry copper" deposit, adjacent to and in the mountains to the east of the Emerald Isle, furnishes the most potent support for postulating that the chrysocolla is supergene. Inasmuch as these primary copper sulfides are known to exist—and their presence is indisputable—it is permissible to think that the chrysocolla has been deposited by solutions derived from the sulfides. This is not an easy explanation, however, despite the fact that chrysocolla is "normally" a supergene mineral. The localization and pattern of deposition of the Emerald Isle copper body must be accounted for, and this is very difficult to do if one postulates a supergene origin.

Mineralized Fissures as Channels for Hypogene Solutions.—The presence of one large vein and numerous sub-parallel veinlets, cutting both bedrock and the overlying blanket of alluvium, is the primary reason for postulating a hypogene source for the mineralizing solutions. Searls has minimized the possibility that these fissures served as avenues for solutions ascending from depth by stating that "as has been pointed out by several engineers, the 'vein' ceases to be a vein below the depth at which it ceases to have the Gila conglomerate on one wall. Below its dip shift the fault is unmineralized." This has little meaning, however, for the termination of a vein at depth is not *a priori* evidence of the mode of formation of its filling. Contrary to this statement of Mr. Searls, however, is the report by Mr. C. F. Weeks,[3] one of the owners of the property, that none of the present workings disclose bedrock in both walls of the vein. At the bottom of the deepest winze, which Mr. Weeks sank in 1942, the hanging wall is still composed of gravel. Therefore the nature of the fault where it passes into bedrock is unknown. There are many smaller mineralized fissures, though, exposed along the walls of the present open pit, which pass into bedrock with no change in size or filling.

Searls agrees that the fissures seem to have been mineralized by ascending solutions, but believes that the solutions rose only from the top of bedrock. As a mechanism for the rise, he suggests that "capillary action and perhaps osmosis has sucked the green water higher along these avenues of better circulation." The possibility of osmotic action obviously can be discarded. The postulation of capillary transport is also illogical for avenues of *circulation*. Furthermore, even if the fissures acted as capillary tubes, the rise caused by surface tension effects would be far short of the vertical range of mineralization above bedrock. For example, copper sulfate will only rise to a height of 3.20 cm (1.26 inches) in a 1.0 mm diameter pore and to 320 cm (10.5 feet) in a 0.01 mm pore. Inasmuch as the main vein has both walls extending above bedrock for approximately 70 feet, the only effective way for the solutions to rise would be under pressure. Conditions for the development of artesian pressure seem to be lacking in the alluvium; therefore the rise of the solutions is most logically explained by hypogene pressure.

Pattern of Deposition in the Alluvium.—Searls states that the "copper minerals coat the pebbles and occur in . . . the bottom layer . . . of the Gila conglomerate." This restriction of mineralization to the lower strata of alluvium is not borne out by the field evidence. Although barren material overlies much of the mineralized ground, chrysocolla occurs all the way from the surface to

[3] Weeks, C. F., Kingman, Arizona, personal communication, 1950.

bedrock in places, notably adjacent to the main vein in the area north of the old No. 1 shaft. Furthermore, wagon-drilling by the Lewin-Mathes Mining Co. showed that concentration of ore values is not confined to the bottom layer, but rather that mineralization is commonly limited to an intermediate layer in the alluvium.[4] This is not in accord with the thesis that the mineralizing solutions first trickled along the bedrock surface, then were "raised by capillary action into the lower layers of the gravel." Rather, the irregular vertical distribution of the chrysocolla can more easily be explained by the lateral migration of solutions from a central source, with the paths of transport determined by differences in the permeability of the poorly stratified alluvium.

Summary.—Present surface drainage from the large sulfide mass is known to carry small amounts of copper in solution. Similar solutions must have existed in the past and conceivably could have deposited the Emerald Isle chrysocolla. However, for such solutions, satisfactory reasons are lacking to explain the areal localization of the deposit and its pattern of deposition.

In contrast, the fissure system provides channels along which solutions could have ascended from depth. If such solutions did exist, the filling of the fissures is easily accounted for, the localization of mineralization in the alluvium follows as a natural consequence, and the pattern of deposition requires no special conditions. Thus, the hypothesis of solutions ascending from depth seems preferable.

BLAKEMORE E. THOMAS.

UNIVERSITY OF KANSAS,
LAWRENCE, KAN.,
Dec. 28, 1950.

Sir: An unfortunate footnote appeared in my paper *A portion of the system silica-water,* which implied that Dr. T. E. Gillingham had available the results shown in Figure 2 of my paper at the time he constructed his hypothetical diagram.[1] This assuredly was not the case and most sincere apologies are offered for the unfortunate inference in the footnote.

GEORGE C. KENNEDY.

[4] Hastings, Earl, Lewin-Mathes Mining Co., personal communication, 1948.

[1] Gillingham, T. E., The solubility and transfer of silica and other non-volatiles in steam: ECON. GEOL., vol. 43, p. 269, 1948.

REVIEWS

De Re Metallica. By GEORGIUS AGRICOLA. Translated by HERBERT CLARK HOOVER and LOU HENRY HOOVER. Pp. 638; 289 woodcuts. Reprinting. Dover Publications, Inc., New York, 1950. Price, $10.00.

This entrancing scientific classic has become famed in the annals of mining, metallurgy, and geology, and its fame and value progressed with that of the translators. The first printing was quite limited and as the value of the copies grew to $150.00 they became treasured in large libraries and collectors shelves. Hence, few people today have seen copies of *De Re Metallica,* but everyone who has read mining and geological journals have seen reproductions of the quaint and fascinating woodcuts. Therefore, this limited reprinting by permission of Honorable Herbert C. Hoover and Mr. Edgar Rickard will be welcomed by all of those whose curiosity has been whetted in the past.

For those who have not seen the book it should be mentioned that the original in latin was first published in 1556 and Herbert Hoover and his wife translated it in 1912, when the limited edition was quickly bought up. The translation and reproduction has been the envy of scholars.

De Re Metallica is stated to be the first book on mining based on field observations and the first to offer detailed technical drawings to demonstrate techniques. The book provides a history of mining from antiquity to the middle of the 16th century. Agricola describes how mineral veins are formed and classified and how alluvial deposits are found and treated. It contains material on mining methods, timbering, surveying, draining mines, sinking shafts, and crushing ore. He also describes assaying, smelting, refining, acid making, and other phases of metallurgy. He has a chapter on the rise of the "witch stick" for finding ores and water, and covers the legal side of mining, boundaries, title forfeiture. Throughout are the many interesting woodcuts depicting geology, mining, and metallurgy.

Any lover of history and particularly geologists, engineers, metallurgists, book collectors, artists, illustrators, and historians will find it of entrancing interest.

Our Oil Resources, Revised 2nd Edit. LEONARD M. FANNING, Editor. Pp. 420; figs. 70; numerous tables. McGraw-Hill Book Co., Inc., New York, 1950. Price, $5.00.

This new edition of a book that had already made a name for itself appears as a completely revised and enlarged volume with many more excellent illustrations. Three new chapters have replaced former ones, new sections are included, and two new chapter contributors are noted, namely, Walter S. Hallanan and Hiram M. Dow.

There are 10 chapters, as formerly, which have been enlarged, brought up to date, and are now rearranged as follows: I, The Role of Private Enterprise in the Development of Oil Resources, by Walter S. Hallanan; II, A National Oil Policy for the United States, Formulated by the National Petroleum Council at the Request of the Secretary of the Interior; III, American Oil Companies in Foreign Petroleum Operations, by Eugene Holman; IV, Conservation of Our Oil and Gas

Resources, by Hiram M. Dow; V, Technology—The Great Multiplier, 1, Exploration Technology, by O. D. Donnell, 2, Production Technology, by John M. Lovejoy; VI, Our Oil and Natural-Gas Resources, 1, The Earth's Petroleum Resources, by Wallace E. Pratt, 2, Estimate of United States Oil Reserves and Natural-gas Liquid Reserves, by the American Petroleum Institute, 3, Estimate of United States Natural-gas Reserves, by The American Gas Association, 4, More Oil for America, by L. F. McCollum, 5, Long-term Availability of Petroleum Report, by The Subcommittee on Long-term Availability, National Oil Policy Committee, American Petroleum Institute, 6, How the Oil-supply Problem Was Licked, by Robert E. Wilson; VII, Our Supplemental Petroleum Reserves, by Eugene Ayres; VIII, The Bureau of Mines Demonstration Plants in the Synthetic-fuels Picture, by L. L. Hirst, J. A. Markovits, R. G. Dressler, and H. R. Batchelder; IX, Capital Employed in the Petroleum Industry, by Joseph E. Pogue and Frederick G. Coqueron. Chapters II and X are new and chapters VII and VIII replace old chapters VI and VII.

The various chapters present an up-to-date survey of oil resources, exploration, technology, private initiative, oil shortages, oil potentialities, possible reserves on the continental shelves, and advances and developments in the oil industry.

This volume will serve as a general reference and is suitable for collateral reading in any course on petroleum geology.

Sourcebook on Atomic Energy. By SAMUEL GLASSTONE. Pp. 546; figs. 115. D. Van Nostrand Company, Inc., New York, 1950. Price, $2.90.

This sourcebook is authorized and prepared under the direction of the Technical Information Service of the U. S. Atomic Energy Commission. It is the first comprehensive book on atomic energy for the use of authors, writers, and scientists, and apparently supersedes the "Smyth Report." The author, a scientist, chemist, and consultant for the A.E.C., was chosen by the Commission who placed at the author's disposal various files and entry into laboratories. The manuscript was reviewed by several scientists for technical accuracy and was also reviewed by the Commission to make certain that publication would not prejudice national security. It is written in a manner to provide a source of basic atomic energy information for everyone who is interested in it, particularly teachers, students and authors. It is rather unusual that the publisher was chosen by competitive bidding.

Eighteen chapters cover such phases as the foundations of the atomic theory, the structure and constituents of the atom, energy, radiations, and natural radioactivity. It also covers isotopes, charged particles, the neutron, fission, new elements, utilization of nuclear energy and isotopes, cosmic rays and mesons, and radiation protection.

Although written in narrative form, without "popularizing," it presents the spectacular story of the achievement of modern science in which everyone is interested today.

World Geography of Petroleum. Edited by WALLACE E. PRATT and DOROTHY GOOD. Pp. 464; figs. 60; tbls. 30; pls. 98. Amer. Geogr. Soc. Special Pub. 31. Princeton University Press, Princeton, N. J., 1950. Price, $7.50.

This very comprehensive discussion of world oil is a combination of geography and geology by 21 expert petroleum geologists and technicians, with 50 new maps prepared by the American Geographical Society.

Following "A Geologist's Foreword," by Wallace E. Pratt, is Part I, Petroleum in the Ground, by Eugene Stebinger, covering geological principles governing the ocurrence of petroleum—origin, traps, search, geological and geophysical exploration, results, estimation of reserves, and tables of production and reserves as of 1949.

Part II, The Functional Organization of the Petroleum Industry, by William B. Heroy, discusses the organization of the petroleum industry, including development, drilling, production, storage, transport, refining, and distribution.

Part III, The World's Petroleum Regions, is in 16 parts by the following authors: Wallace E. Pratt, Guillermo Zuloaga, A. J. Freie, Oliver B. Knight, Geoffrey Barrow, Frank B. Notestein, A. I. Levorsen, G. M. Lees, Max Steineke and M. P. Yackel, Eugene Stebinger, Lyman C. Reed, I. Swemle, and D. Dale Condit. This part covers all the chief oil areas of the world and gives broad features of the geology and the geography. It is finely illustrated by excellent maps and striking photographs.

Part IV, Aspects of Utilization, consists of 5 parts as follows: Availability of Petroleum, by Kirtley F. Mather; Geographical Aspects of Petroleum Use in World War II, by the Army-Navy Petroleum Board; World Pattterns of Civilian Utilization, by John W. Frey; Statistical Survey, by Anastasia Van Burkalow; Effect of World Distribution on the Power and Policy of Nations, by Herbert Feis.

An appendix covers world regions, production and exports, bibliography, abbreviations, glossary, conversion factors, and index.

The above summary of contents indicates the wide and authoritative coverage, which is supplemented by some 30 tables. The extended bibliography of the geology of the oil regions is a valuable and useful addition. The book is bound to appear on the shelves of all of those interested in the geography and geology of petroleum.

A Practical Handbook of Water Supply. By FRANK DIXEY. Pp. 573; maps 6; figs. 133. Thomas Murby & Co., London, 1950. Price, 35 s.

This volume is the sixth relating to hydrology and water supply that has received attention in these columns in the last two years. This second edition, appearing almost 20 years after the first edition, brings up to date the many aspects of water supply problems. Like its predecessor it is concerned less with the problems of large water supplies for industrial and municipal purposes, but relates rather to fundamentals and use of minor water supplies. As might be expected, the author's extended experience in Africa has been drawn upon in supplying much of the text material.

This second edition carries some degree of revision, brings the former material up to date, and incorporates many new references to permit access to the reader of fields in which he might be interested. The chapter headings remain about the same. They are: 1, Water Resources; 2, 3, Surface Water Supply; 4, Ground Water Supply; 5, Quality of Water; 6, Water-Finding Methods; 7, Recovery of Ground Water; 8, Water Supply Conditions in Parts of Africa. Chapters 2 to 5 have undergone little revision, and in the others later information has been incorporated.

This edition will continue to serve the practical purposes of the first volume, particularly for the drier tropical and subtropical regions.

BOOKS RECEIVED.

CHARLES H. SMITH.

U. S. Geological Survey—Washington, D. C., 1950.

Prof. Paper 142-I. The Molluscan Fauna of the Alum Bluff Group of Florida. JULIA GARDNER. Pp. 52. Price, 35 cts. *Part IX, index to chapters A-H.*

Prof. Paper 221-G. Pre-Wisconsin Soil in the Rocky Mountain Region—A Progress Report. CHARLES B. HUNT AND V. P. SOKOLOFF. Pp. 14; figs. 4. Price, 15 cts. *A study of ancient soils in the Lake Bonneville and Denver Basins.*

Bull. 955-E. Fluorspar Prospects of Montana. CLYDE P. ROSS. Pp. 51; figs. 4; pls. 10. Price, $1.00. *A summary of available information. The occurrences are fairly numerous and widely distributed, but few deposits are known to be of high grade and most appear to be small and irregular in shape.*

Bull. 963-B. Copper Deposits of the Prince William Sound District, Alaska. FRED H. MOFFIT AND ROBERT E. FELLOWS. Pp. 33; pls. 4; fig. 1. Price, 75 cts. *An account of the present state of the prospects, extent of development, and condition of equipment in an inactive mining area.*

Bull. 963-C. Garnet Deposits near Wrangell, Southeastern Alaska. C. T. BRESSLER. Pp. 12; pls. 2; fig. 1. Price, $1.00. *Almandite garnet crystals disseminated in schists near a quartz diorite stock.*

Bull. 974-A. The 1949 Summit Eruption of Mauna Loa, Hawaii. GORDON A. MCDONALD AND JAMES B. ORR. Pp. 33; figs. 15. Price, 20 cts. *The history of the eruption, eruptive products, and accompanying phenomena, illustrated by many photographs.*

Bull. 976-C. Geophysical Abstracts 142, July–September 1950. MARY C. RABBITT AND S. T. VESSELOWSKY. Pp. 68. Price, 25 cts. *Nos. 12126 to 12339.*

Water Supply Paper 1095. Surface Water Supply of Hawaii, 1946–47. Under the direction of C. G. PAULSEN. Pp. 130. Price, 35 cts.

Manual of Analytical Methods for the Determination of Uranium and Thorium in Their Ores. Pp. 55. Atomic Energy Commission, U. S. Government Printing Office, Washington 25, D. C., September 1950. Price, 20 cts. *A compilation of 8 chemical methods for the analysis of pitchblende, carnotite-bearing sandstone, shales, phosphate rock, and monazite sands.*

Illinois Geological Survey—Urbana, 1949–1950.

Rept. Inves. 141. Fluorspar and Fluorine Chemicals. Part I—Economic Aspects of the Fluorspar Industry. N. T. HAMRICK AND W. H. VOSKUIL. **Part II—Fluorine Chemicals in Industry.** G. C. FINGER AND F. H. REED. Pp. 70; figs. 7; tbls. 21.

Rept. Inves. 149. Loess Formations of the Mississippi Valley. MORRIS M. LEIGHTON AND H. B. WILLMAN. Pp. 24; figs. 9; pls. 2; tbls. 3. *The authors describe the loess deposits of the upper and lower Mississipppi Valley and find no substantial evidence to support the "loessification" theory of Russell and Fisk.*

Kansas Geological Survey—Lawrence, 1950.

Bull. 86, Part 6. Subsurface Reconnaissance of Glacial Deposits in Northeastern Kansas. JOHN C. FRYE AND K. L. WALTERS. Pp. 17; pls. 2; map 1. *The stratigraphy and water supply of Cenozoic deposits.*

Bull. 88. Geology and Ground-Water Resources of Barton and Stafford Counties, Kansas. BRUCE F. LATTA. Pp. 228; figs. 18; pls. 11; tbls. 13.

Ohio Department of Natural Resources—Columbus, 1950.

Bull. 19. The Water Resources of Greene County, Ohio. STANLEY E. NORRIS, WILLIAM P. CROSS AND RICHARD P. GOLDTHWAIT. Pp. 52; pls. 23; tbls. 8.

Bull. 21. Ground-Water Levels in Ohio, 1948. PAUL KASER. Pp. 60; pls. 32; tbls. 44.

Seventh Biennial Report of the Oregon Department of Geology and Mineral Industries. Pp. 25. Bull. 42, Portland, 1950.

Crude Oil Reserves of Pennsylvania. WILLIAM S. LYTLE. Pp. 256; tbls. 7; pl. 1; fig. 1. Pennsylvania Topog. and Geol. Survey Bull. M-32, Harrisburg, 1950. *Estimated that 2,734,434,000 barrels of oil remain in the known reservoirs.*

Texas University Publication—Austin, 1950.

No. 5020. Utilization of Texas Serpentine. VIRGIL E. BARNES, D. A. SHOCK, AND W. A. CUNNINGHAM. Pp. 52; figs. 19; tbls. 17; map 1. *In 4 parts: 1, serpentine deposits; 2, minerals, composition and structure of serpentine; 3, experimental data on serpentine; 4, review of possible industrial uses of serpentine, with bibliography.*

Rept. Inves. 7. Subsurface Woodford Black Shale, West Texas and Southeast New Mexico. SAMUEL P. ELLISON, JR. Pp. 20; figs. 6; pls. 3. *Describes and illustrates the geographic distribution, lithology, thickness and paleontology of the Woodford in the Permian basin.*

Infrared Spectra of Reference Clay Minerals. HANS H. ADLER, PAUL F. KERR, ELLIS E. BRAY, NELSON P. STEVENS, JOHN M. HUNT, WALTER D. KELLER, AND E. E. PICKETT. Pp. 146; pls. 72; tbls. 11. Am. Petroleum Inst. Project 49, Clay Mineral Standards Prel. Rept. 8, Columbia Univ., New York, 1950. *The last of a series of preliminary reports on reference clay minerals. This report represents an assembly of experimental data concerning the infrared absorption characteristics of clay minerals.*

Technical Publications 1948. ARMAN E. BECKER, Editor. Pp. 512. Standard Oil Co., N. J., and Affiliated Companies, 1950. *A group of 24 papers under following headings: geology and production; manufacturing and fuel quality; rubber and plastics; analysis.*

Irrigation Principles and Practices, 2nd Edit. ORSON W. ISRAELSEN. Pp. 405; figs. 179; tbls. 50. John Wiley & Sons, New York, and Chapman & Hall, London, 1950. Price, $6.00. *Fundamental aspects of irrigation principles and practices with newer information since the first edition of 1932. New material on flow of water in soils, drainage, use of water, hydraulic equations, and irrigation in arid lands; of interest to geologists.*

Pleistocene Geology of the Lake Simcoe District, Ontario. R. E. DEANE. Pp. 108; figs. 9; pls. 14; maps 2. Canada Geol. Survey Mem. 256, Ottawa, 1950. Price, $1.00. *Land forms, bedrock and unconsolidated material comprising them, and the origin and mode of accumulation of glacial deposits described. Relates historical events following retreat of last ice sheet, the inundation by glacial Lake Algonquin and post-glacial uplift.*

Bibliography of Seismology, No. 7, Items 7222–7417, January to June 1950. W. G. MILNE. Pp. 17. Dominion Observatory Pub., Vol. XIV, Ottawa, 1950. Price, 25 cts.

Geology of the Gullwing Lake-Sunstrum Area. W. D. HARDING. Pp. 29; figs. 12; colored geol. map, scale 1″ = 1 mile. Ontario Dept. Mines 59th Annual Rept., Vol. LIX, Part IV, 1950, Toronto, 1951. *Volcanics, sediments, and lamprophyre cut by Algoman granitic complex. No economic mineralization.*

The Australian Mineral Industry—1949 Review. Pp. 186. Australia Bur. Min. Resources, Geology and Geophysics, Melbourne, 1950. *Production statistics.*

Report of the Geological Survey of Western Australia for the Year 1947. Pp. 60; pls. 9; colored maps; tables. Perth, 1950. *Administrative material and reports on mineral deposits.*

South Africa Department of Mines—Pretoria, 1948.

The Geology of the Country Around Messina. P. G. SÖHNGE, H. D. LE ROEX, AND H. J. NEL. Pp. 74; pls. 12; fig. 1; colored map, scale, 1:125,000. *The area is underlain by rocks of the Archean complex and Karroo system and post-Karroo intrusives. Although a number of minerals are listed as occurring in the area, copper mining dominates. The occurrences are only briefly described.*

The Geology of the Schoorsteenberg Area, Cape Province. J. J. G. BLIGNAUT, P. J. ROSSOUW, J. DE VILLIERS, AND H. D. RUSSELL. Pp. 40; fig. 1; pl. 1; colored map, scale, 1:125,000. *Karroo and Tertiary deposits, dolerite intrusions. Area offers no possibilities of mineral exploitation.*

Minerales. Pp. 37. Inst. ing. Chile rev. July–Sept. 1950. Santiago. *Includes a report on the coal mine "Colico Sur" by Carlos Neuenschwander.*

Atlas of Denmark. NIELS NIELSEN, Editor; AXEL SCHOU. 2 vols. Text, pp. 129; 91 photographs. Royal Danish Geogr. Soc., Copenhagen, 1949. *The morphology of Danish landscapes and their distribution are described under the following headings: glacial, moraine, granite, valley, basalt, and dune landscapes, landscape forms of meltwater deposits, the marine foreland, and the coasts. Illustrated with many fine photographs.* Atlas volume, pp. 32. *This volume is coordinated with the text, and provides excellent block diagrams and maps illustrating in great detail the distribution and the evolution of the landscapes described in the text.*

Atlas du Katanga, 2nd part, Lukafu Area. Pp. 30; maps 10; photographs 14. Comité Spécial du Katanga, Bruxelles, 1950. *Colored geodetic, geologic, hypsometric, soil and vegetation maps on scale of 1/400,000; topographic, soil, and geologic maps on scale of 1/200,000; hypsometric and geologic maps of central Katanga on scale of 1/100,000. Each map is described in the accompanying text.*

Annales de la Société Géologique de Pologne—Cracow, 1949–1950.

Vol. 18. Pp. 356; many illustrations. *Papers on zeolites; crystalline exotic blocks in the Silesian Cretaceous of the Wadowice area; new or little known foraminifera in the Flysch of the Polish Carpathians; the microfauna of the Lower Cretaceous near Tomaszów Mazowiecki (Central Poland); problems of stratigraphy of marine Triassic in the Cracow area; Lower Tortonian at Benczyn near Wadowice; dolomitization of Jurassic limestones near Cracow.*

Vol. 19, Fasc. 2. Pp. 107; many illustrations. *Papers on the Miocene near Lublin; the age of variegated marls in the Flysch of the Western Carpathians; some siliceous rocks in Poland; new facts concerning the ice-transported block of the Jurassic at Luków; littoral deposits of the Middle Jurassic south of Krzeszowice.*

Vol. 19, Fasc. 3. Pp. 76; many figures. *Papers on the Koperszady conglomerate and the Murán limestone; the Cenomanien near Cracow; geological maps of the folds in the Iwonicz-Klimkówka-Rymanów area; sulfate weathering products on the iron disulfide deposit at Rudki.*

SCIENTIFIC NOTES AND NEWS

JAMES DOUGLAS, Secretary of Phelps Dodge Corporation, has been appointed Acting Deputy Administrator of the Defense Minerals Administration in Washington, D. C.

E. C. STEPHENS, geologist for Anaconda Copper Mining Co., has been elected president of the Northwest Mining Association. He succeeds H. J. HULL, of Wallace, Idaho. DAVID E. WATSON, secretary of the Thomas Mines, is first vice president; WALLACE G. WOOLF, general manager of the Sullivan zinc plant at Kellogg, second vice president; E. K. BARNES, treasurer, and ROGER O. OSCARSON, mining engineer, secretary.

The 19th International Geological Congress, meeting in Algiers in 1952, will carry a Symposium on Iron. They are asking various countries to submit information regarding the preparation of material for the symposium. They are also asking prospective authors to submit two copies of each paper by December 31, 1951. The several chapters suggested for the Symposium are as follows: Generalities on iron ore deposits; geographical and geological distribution of iron ore deposits; geological description of iron ore deposits; genesis of iron ore deposits; estimate of reserves of iron ore; statistical data; historical and economic data; bibliography.

The "Association for the Study of the Paleontology and the Stratigraphy of the Coal Measures" was founded in 1943 by Prof. V. Van Straelen, Director of the Royal Institute of Natural Sciences of Belgium, with the help of Belgian finance and industry. Since 1946 the Association has drawn its funds from various private industrial concerns and from the State.

As implied in its title, the Association's first concern is to develop Belgian knowledge regarding the fossils contained in the Coal Measures; thence to draw up more accurate and more reliable stratigraphical columns of already well known sequences in the five Belgian coal districts. Attempts will be made to solve stratigraphical problems, and also of tectonics, in less well known areas of the coal fields. Petrographical studies are also undertaken. The Association is running with a team of field geologists, whose main job lies within the coal mines, and a team of laboratory workers, who carry out specialized research work in Brussels; a staff of fully trained technical workers assists the scientists. Six memoirs have been published so far.

The Association is located on the premises of the "Royal Institute of Natural Sciences of Belgium," 31 Vautierstreet, Brussels.

ALFRED D. WANDKE and ARTHUR R. STILL have recently set up an office in Prescott, Arizona, under the title of Southwestern Geological Service. Both men are graduates of the University of Arizona and have, since graduation, been engaged in graduate work at Harvard University where Wandke received his Doctor's degree and Still his Master's degree in 1950. They propose to undertake geologic and other types of mapping for mines which do not have established geological departments, and they are equipped to make microscopic examinations of ore and mill products.

LOWELL B. MOON, of the U. S. Bureau of Mines, has been appointed chief of the Minerals Division of the Bureau of Mines to succeed JOSEPH H. HEDGES, who has been appointed special assistant to Bureau Director James Boyd. As chief of the Minerals Division, Mr. Moon will be in charge of that part of the Bureau of Mines whose emergency mission is to work closely with the Defense Minerals Administration in expanding mineral production.

The Wyoming Geological Association will hold its Sixth Annual Field Conference, July 31 to August 3 inclusive, in the South Central part of Wyoming. Areas such as Separation Flats, the Ferris, and Seminoe Mountains, and the Sweetwater and Rawlins uplifts, will be included in the daily field trips. Headquarters for the trip will be set up in Rawlins, Wyoming. R. W. Mallory of the Stanolind Oil and Gas Co. is the General Chairman.

EDWARD WISSER and K. G. SCHWEGLER announce their association as Wisser and Schwegler, Mining and Geological Consultants, at their new offices, 422 Acheson Building, 2131 University Avenue, Berkeley 4, California.

G. SÖHNGE has been transferred from Nababeep, Cape Province, to Tsumeb, South West Africa, where he is employed as Chief Geologist to the Tsumeb Corporation, Limited.